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2024 has been an exciting year for space exploration, with a host of discoveries being made by telescopes right here on Earth to spacecraft venturing beyond the boundaries of our Solar System. Technological advancements have allowed us to peer back to the very dawn of time to spy on the earliest galaxies, while we're also getting closer to solving the secrets of the dark universe with newly launched missions like Euclid. Hubble and the James Webb Space Telescope continue to amaze with their deep-reaching imagery of galactic phenomena, while astronauts are training hard to return to the Moon and gearing up for Mars exploration in the near future. Inside this year's **All About Space Annual**, you'll blast off on a journey from low-Earth orbit all the way to the deepest reaches of the cosmos.

FUTURE

ALL ABOUT SPACE Annual

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All About Space Editorial
Editor-in-Chief **Gemma Lavender**
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International
Head of Print Licensing **Rachel Shaw**
licensing@futurenet.com
www.futurecontenthub.com

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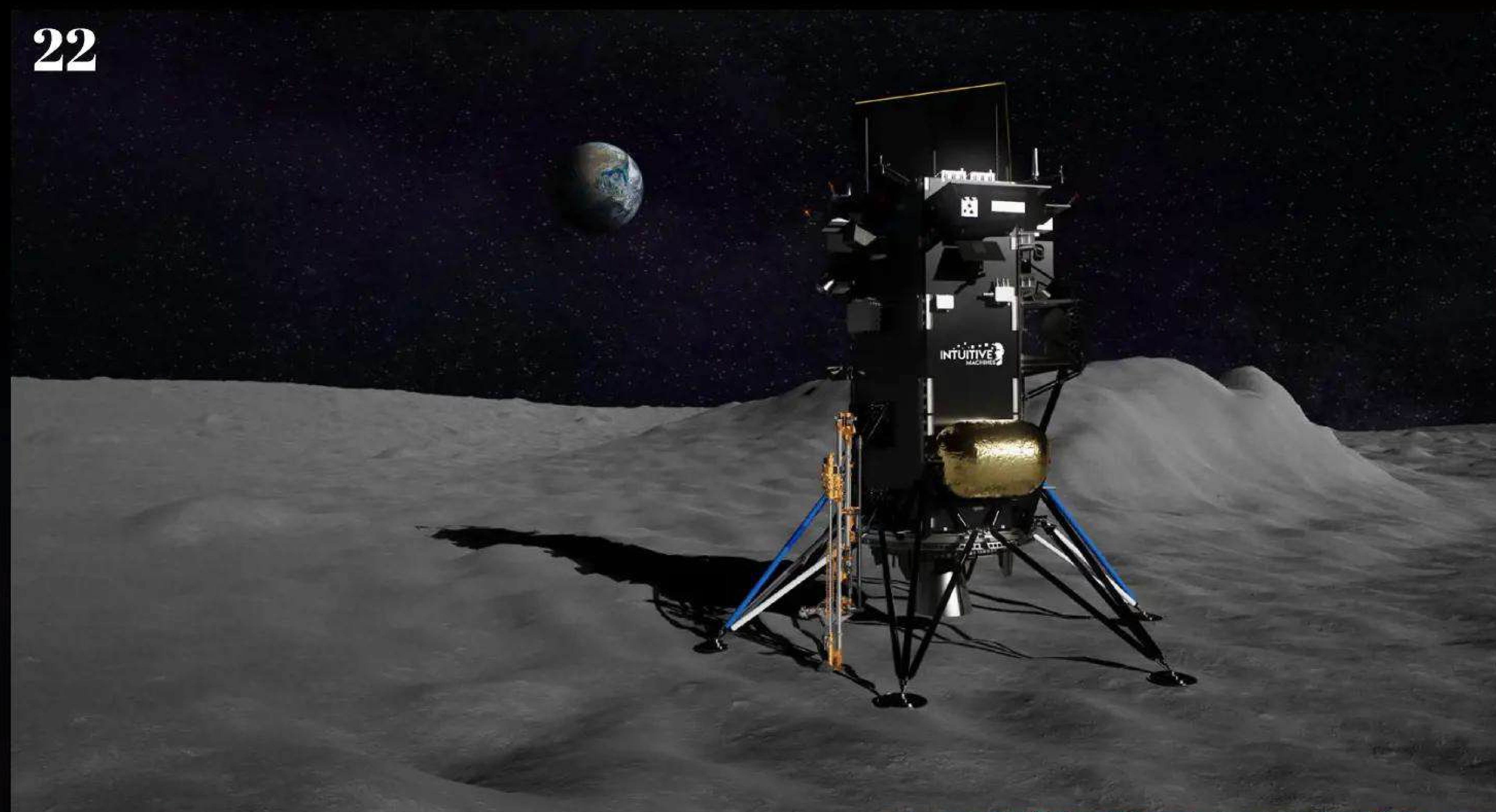

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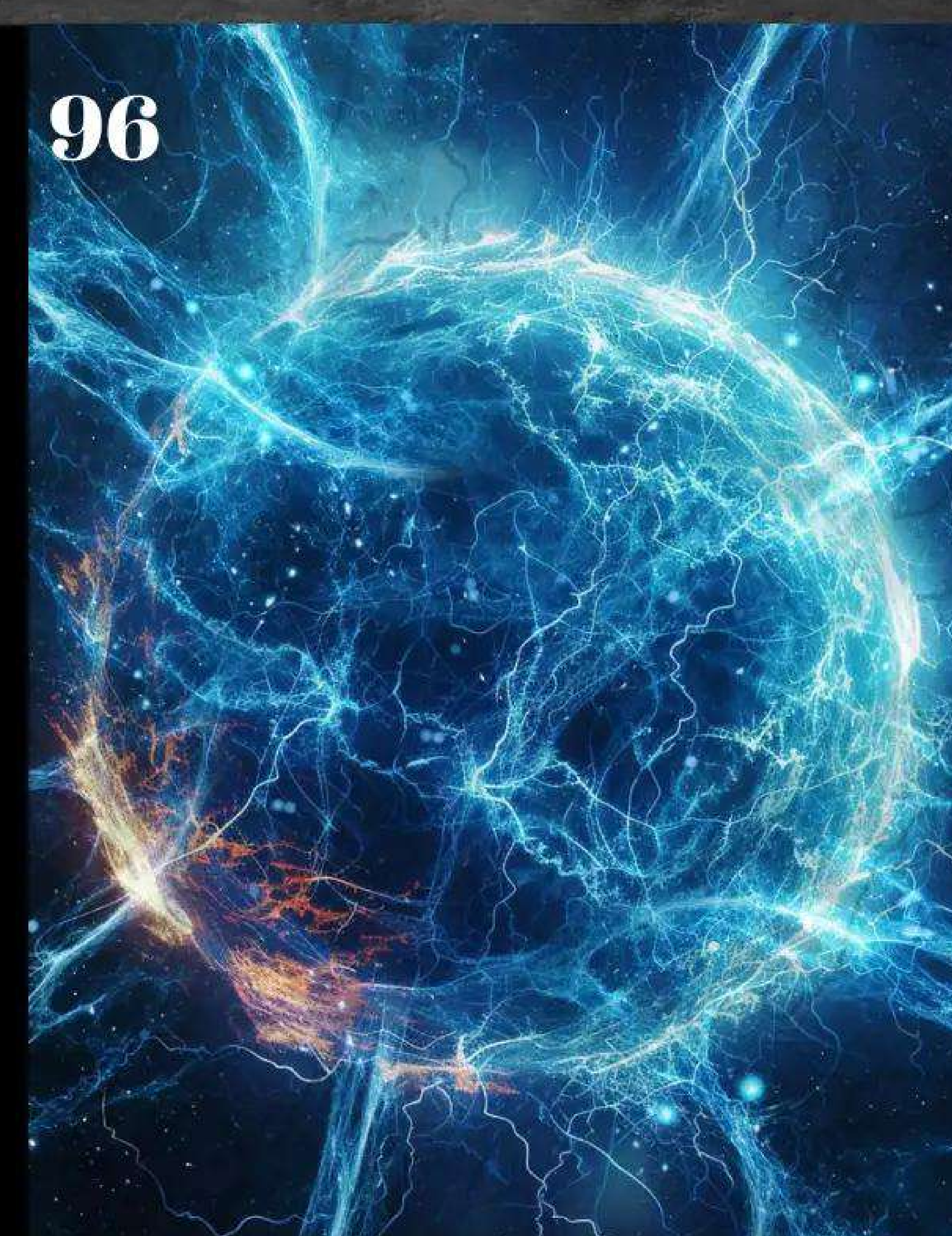

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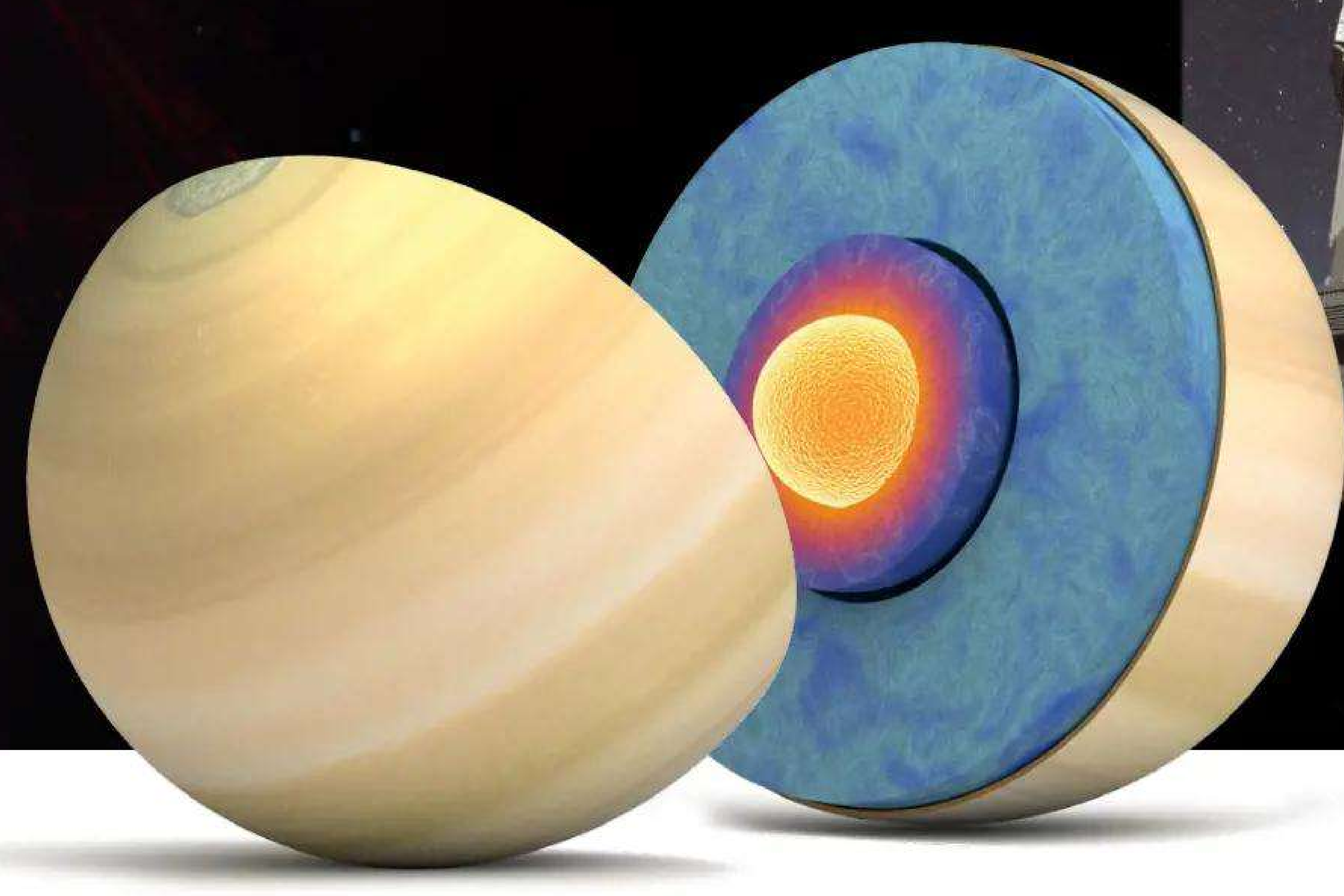

SOLAR SYSTEM

Discover the secrets of our fascinating planetary system

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> "Jupiter was the first planet to form in the protoplanetary nebula"

FOCUS ON

MAGNETIC FIELDS ON THE SUN COULD SOLVE A LONG-STANDING SOLAR HEATING MYSTERY

Scientists still aren't sure why the corona is so much hotter than the Sun's surface

Reported by Sharmila Kuthunur

Scientists have long wondered why the hot soup of charged particles in our Sun's atmosphere gets hotter moving away from the surface of the Sun. New research may have the answer, finding the superhot nature of the Sun's outer atmosphere, or corona, could be due to the intriguing behaviour of small-scale waves in this nebulous plasma. These waves, known to scientists as kinetic Alfvén waves (KAWs), are wave-like vibrations of magnetic fields manifested by motions in the Sun's photosphere. The findings could provide an important clue to decoding the physics-defying coronal heating mystery of why the corona is hundreds of times hotter than the visible solar 'surface', or photosphere, that radiates all the light we see from the Sun. The team behind this research, led by Syed Ayaz, a researcher at the University of Alabama in Huntsville, theorises that as KAWs propagate, they dissipate and heat the Sun's corona, serving as an important mechanism by which energy is transferred within the Sun's plasma. "For decades, Alfvén waves have been proven to be the best candidates for transporting energy from one place to another," Ayaz said.

The majority of the Sun's energy comes from its core, where nuclear fusion occurs. That means the Sun should get hotter as you move deeper within it. Most of the layers of our star obey this principle. However, the corona, despite being millions of miles further away from the solar core than the Sun's surface, is still vastly hotter than the photosphere. Ayaz and his colleagues studied the influence of KAWs in the plasma floating up to an altitude equal to ten times the Sun's radius. At such distances, when the waves interact with the Sun's charged plasma, which is packed with ions – atoms that have been stripped of their electrons – they "rapidly dissipate, completely transferring their energy to plasma particles in the form of heating," Ayaz said.

^ The corona can only be viewed from Earth during a total solar eclipse

The findings suggest that energy from the waves can reach the corona and heat it, although just how much they contribute to the temperature of the corona remains to be seen. This new research "offers important insights into the critical problem of how energy in a magnetic field is transformed to heat a plasma comprising charged particles like protons and electrons," said Gary Zank, director of the Center for Space Plasma and Aeronomic Research, who was not involved with the work. The findings of the latest study are strengthened by data from the European Space Agency's Solar Orbiter and NASA's Solar Dynamics Observatory (SDO). The SDO previously found that another kind of high-frequency, arch-like magnetic wave propagating through the corona can also dump large amounts of energy into the outer atmosphere of the Sun over time, contributing to the heating of the million-degree-hot layer.

THE SUN'S EFFECT ON THE PLANETS

Whether stripping them away or lighting them up, the atmospheres of our Solar System's worlds are continually shaped by the output of our star

1 Neptune
Aurorae were spotted by Voyager. But the distinct offset between the planet's magnetic field and its rotational axis means these weak light displays can be found across the surface.

2 Uranus
On Uranus the solar wind excites atmospheric hydrogen to create its aurorae, which can be found close to its geographical equator as the planet orbits on its side.

3 Saturn
Saturn's poles are regularly lit up by strong aurorae, though as they are in the ultraviolet and infrared parts of the spectrum they would be invisible to us.

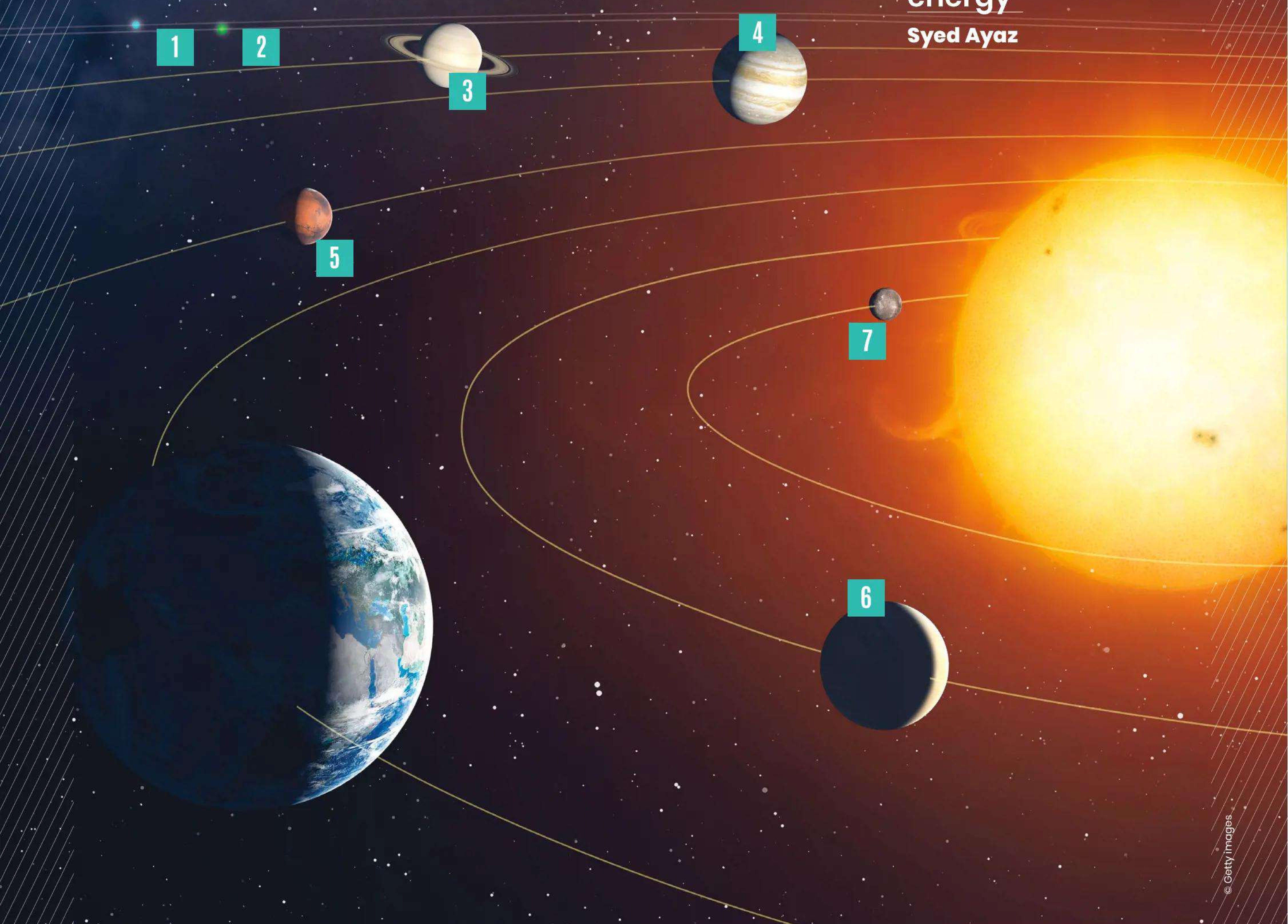
4 Jupiter
Recent data from Juno suggests Jupiter's powerful blue aurorae are not entirely powered by the same solar wind mechanism behind aurorae on the other planets.

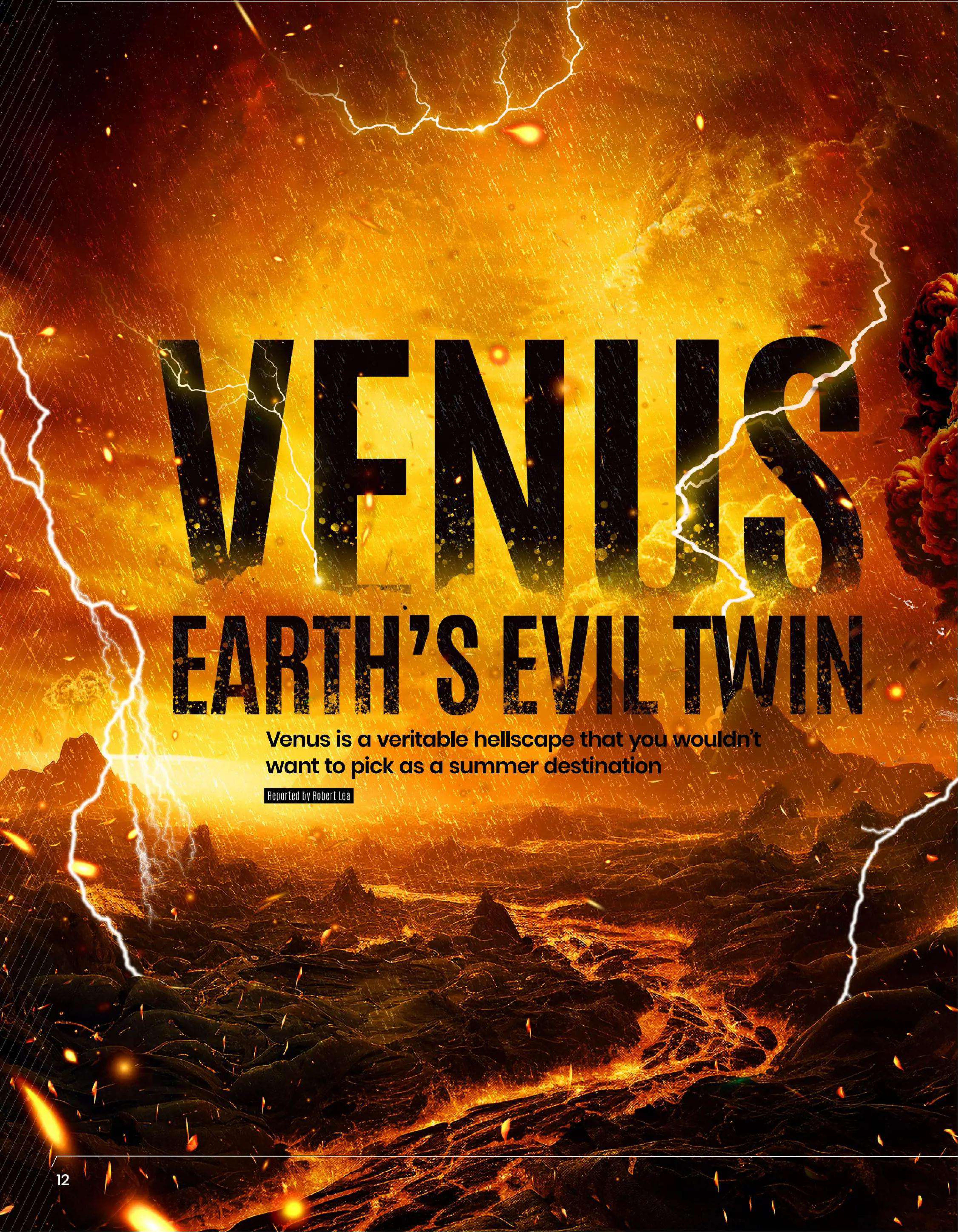
5 Mars
Mars' small size and weak gravitational hold left it unable to cling onto its early thick atmosphere. It was subsequently stripped away over time by the solar wind.

6 Venus
Without a magnetic field, lighter gases from Venus' thick atmosphere, including water vapour, are continuously blown away by the solar wind.

7 Mercury
Its close proximity to the Sun and lack of atmosphere leave its relativity weak magnetic field swamped by solar eruptions and its surface bathed in the radiation of the solar wind.

> **"Alfvén waves have been proven to be the best candidates for transporting energy"**
>
> **Syed Ayaz**





VENUS
EARTH'S EVIL TWIN

Venus is a veritable hellscape that you wouldn't want to pick as a summer destination

Reported by Robert Lea

Venus is the second planet from the Sun and is Earth's closest planetary neighbour. As you might expect from two planets born from the same swirling cloud of gas and dust at roughly similar distances from the infant Sun about 4.6 billion years ago, Venus and Earth are similar in many ways. Both planets are around the same size – Earth is just a little bigger in diameter – and both seem to be composed of the same materials, despite Venus being about 80 per cent as dense as Earth.

In fact, Venus is often referred to as 'Earth's twin', and for good reason. "Venus is unique in our Solar System in lots of ways. In many ways it's similar to Earth, but it's also very different. It's also one of just a few objects in our Solar System with a substantial atmosphere along with Earth, Mars, Titan, Io, and Pluto, and it's by far the one with the thickest, hottest, most intense atmosphere," Eryn Cangi, a research scientist at the Laboratory for Atmospheric and Space Physics at the University of Colorado Boulder tells **All About Space**. "We can learn about terrestrial planets by observing and studying Venus and interpreting it as an extreme case of what can happen on terrestrial planets."

Yet before you plan a future trip to Venus – it's only an 80-million-kilometre (50-million-mile) round trip, after all – there are a few things you need to consider. When it comes to the habitability of both planets, something seems to have gone horribly wrong in the evolution of Venus, which means perhaps the moniker 'Earth's evil twin' is much more appropriate. "Venus is the closest planet to Earth, and still we know so little about it," European Space Agency (ESA) scientist Håkan Svedhem says. "Venus was likely very similar to Earth after the formation of the Solar System, but it has evolved in a very different direction."

> **"Venus is unique in our Solar System in lots of ways. In many ways it's similar to Earth, but it's also very different"**
>
> **Eryn Cangi**

While holidaymakers actively seek out high temperatures, the mean surface temperature of 464 degrees Celsius (867 degrees Fahrenheit) is enough to cause your luggage to burst into flames. In fact, as the hottest planet in the Solar System, temperatures on Venus are hot enough to melt any lead items you pack, too. Venus isn't as close to the Sun as the tiny planet Mercury, yet it is much hotter. Mercury is relatively balmy at 430 degrees Celsius (800 degrees Fahrenheit), with nighttime temperatures dropping to -180 degrees Celsius (-290 degrees Fahrenheit) because of the tiny planet's lack of atmosphere. Clearly, it isn't just proximity to the Sun that makes Venus so much hotter than Earth… something else must be at play.

The thick atmosphere of Venus is composed mostly of carbon dioxide, which as we are all too familiar with on Earth is one of the main drivers of climate change and the warming of our planet. Greenhouse gases are composed of atoms that are capable of absorbing infrared radiation from the Sun. While this is a key element of allowing a planet to stay temperate, an

INSIDE VENUS

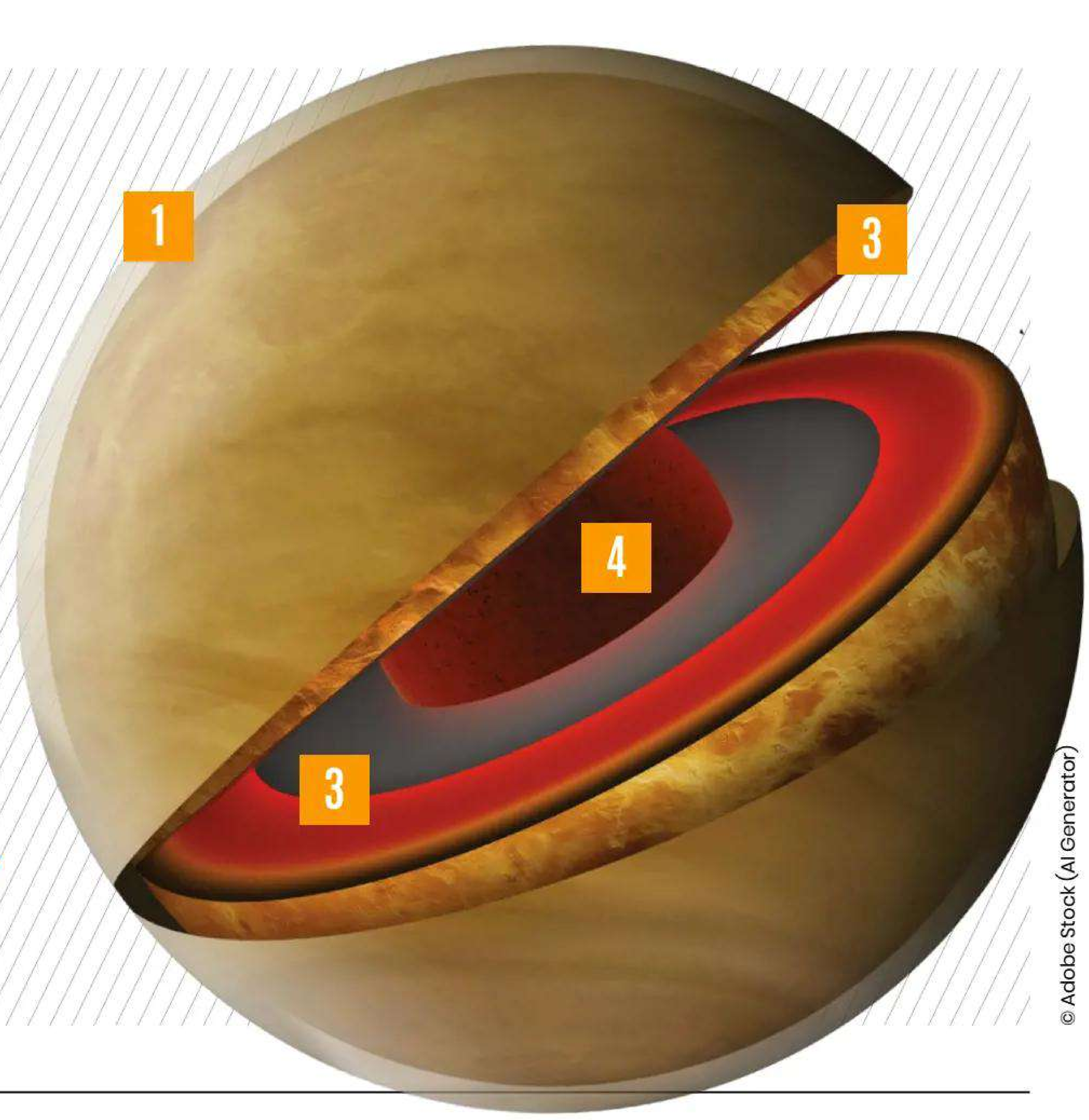
What makes up this hellishly hot world?

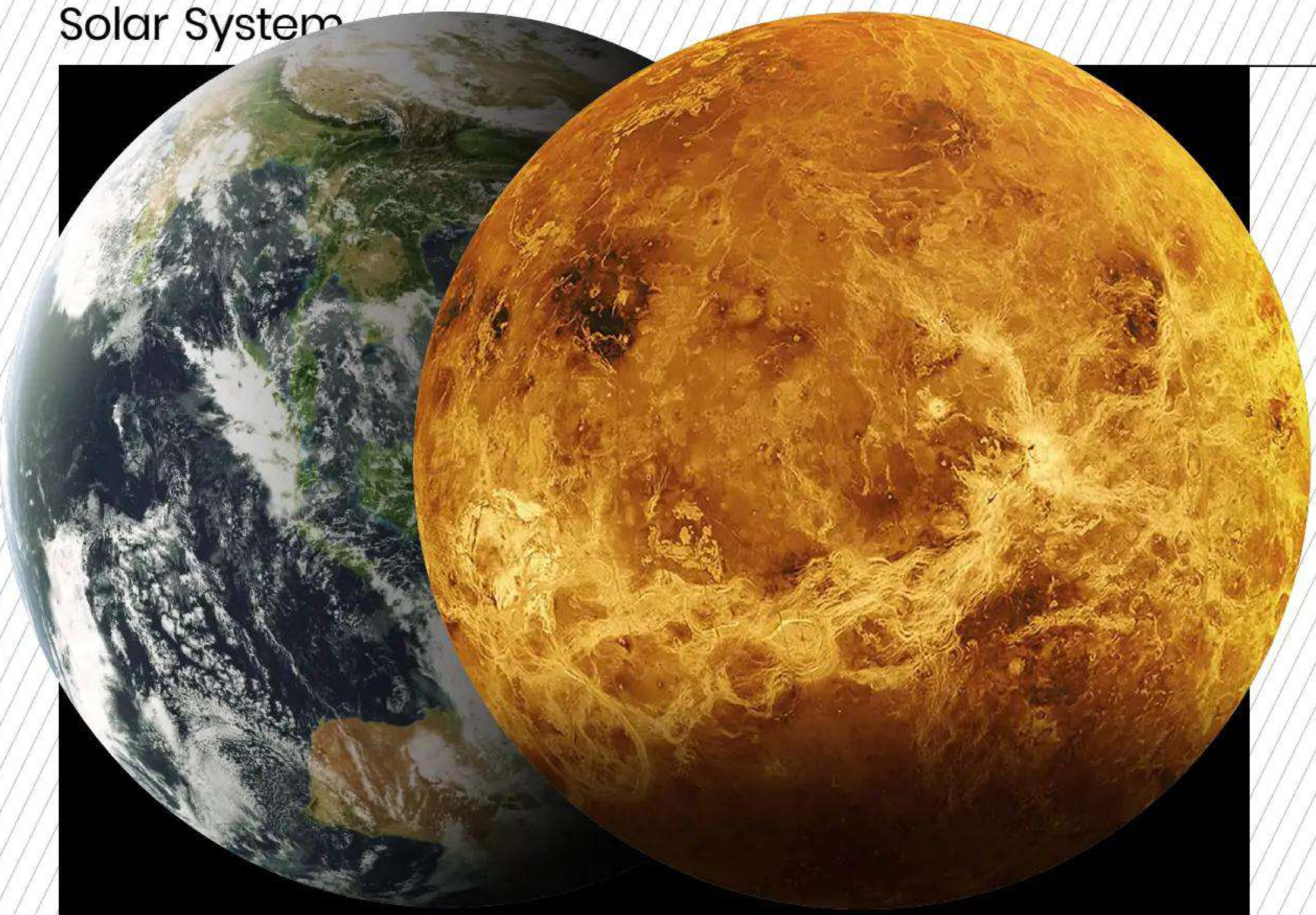
1 Atmosphere 96.5 per cent of Venus' atmosphere is carbon dioxide, with 3.5 per cent being nitrogen.

2 Crust Venus' crust is made of silicate rocks and is estimated to be 50 kilometres (31 miles) thick.

3 Molten mantle The heat from the core creates a molten mantle that is 3,000 kilometres (1,864 miles) thick.

4 Metallic core Venus' iron core consists of a solid inner and liquid outer core roughly 3,200 kilometres (1,990 miles) in radius.





EARTH VS VENUS

Sometimes called 'Earth's twin', Venus is a very different world to ours

Earth		Venus
150 million kilometres (93 million miles)	**Average distance from the Sun**	108 million kilometres (67 million miles)
6,378 kilometres (3,963 miles)	**Planet radius**	6,052 kilometres (3,760 miles)
5,520 kilograms per cubic metre	**Planet density**	5,250 kilograms per cubic metre
15 degrees Celsius (59 degrees Fahrenheit)	**Surface temperature**	465 degrees Celsius (869 degrees Fahrenheit)
78% nitrogen, 21% oxygen, 1% argon	**Atmospheric composition**	96.5% carbon dioxide, 3.5% nitrogen

abundance of greenhouse gases leads to a runaway greenhouse effect.

Scientists at NASA's Goddard Institute for Space Studies estimate that for around 2 billion years Venus had a shallow liquid-water ocean and habitable surface temperatures. Today, however, Venus has 100,000 times less water than Earth, even though it's roughly the same size and mass. "It's not proven, but scientists think the atmosphere of Venus started in a similar stage as that of the early Earth," Svedhem says. "As Venus is closer to the Sun, the water vaporised and helped heat up the atmosphere even more."

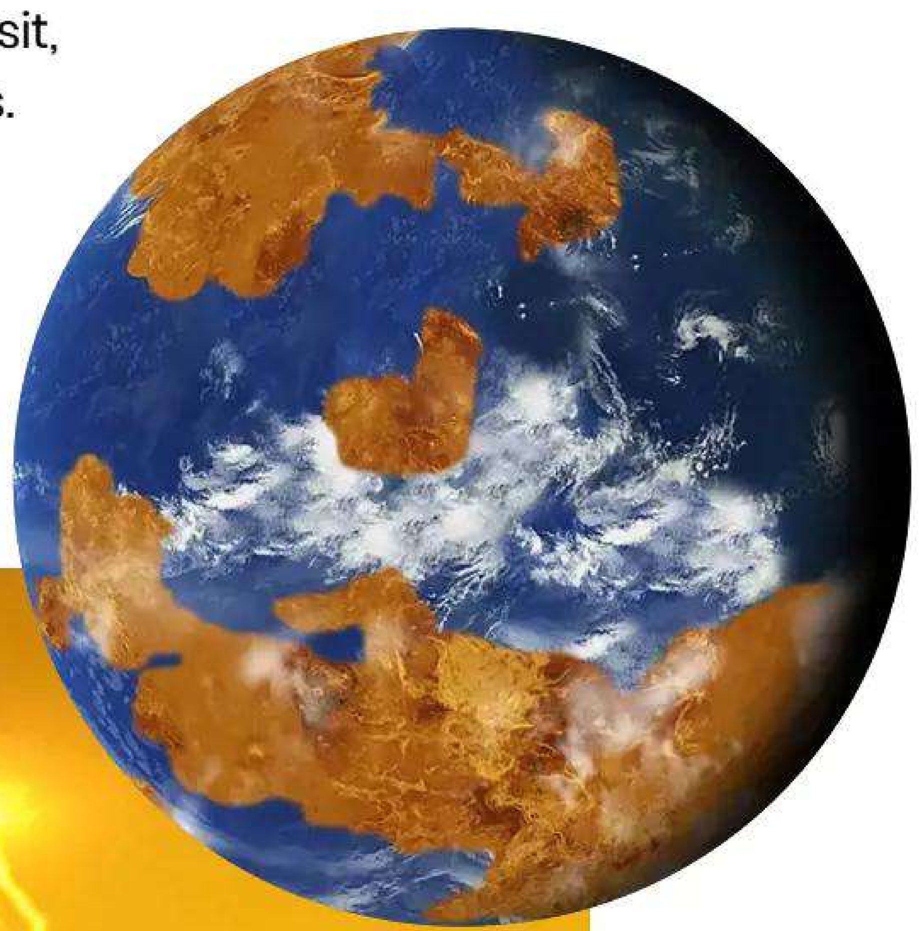
Svedhem adds that this is because water vapour is a very strong greenhouse gas – much stronger than carbon dioxide. As water vapour filled Venus' atmosphere, the planet's temperature continued to rise due to this greenhouse effect. This resulted in carbon dioxide being 'cooked out' of Venus' carbon-rich rocks, with the addition of large volumes of this other powerful greenhouse gas strengthening that effect and causing the temperature to increase even more and resulting in the fearsome conditions Venus has today. These are temperatures that not even the most advanced spacesuit or firefighting equipment could resist.

The idea of a holiday is to avoid pressure, but your break to Venus would expose

you to atmospheric pressures at the surface of 92 bar, which is 92 times greater than Earth's surface pressure at sea level. In fact, it's a bit like swimming down to a depth of just over 800 metres (2,624 feet) in the ocean. And there's something else Venusian holidaymakers would have to brave. In 1974, the Mariner 10 probe found that winds on Earth's evil twin reached speeds as great as 160 kilometres (100 miles) per second. That's 580,000 kilometres (360,000 miles) per hour, which is 250 times faster than the top speed of a Lockheed Martin F-16 jet fighter. And that's just at the cloud tops of Venus. The winds of Venus increase closer to its surface, so there's no way you're putting that beach umbrella up.

The crazy thing about the planet next door is that it spins so slowly that a day on Venus lasts 243 Earth days, but Venus only takes 225 Earth days to complete an orbit of the Sun. That means a day on Venus is longer than a year. "Venus rotates clockwise rather than counterclockwise, so the Sun sets in the east and rises in the west," Cangi says. "This rotation is also very slow; it takes longer than a Venus year for the planet to rotate once on its axis, and its solar day – the time it takes for the Sun to return to the same place in the sky – is about half the length of its year."

In addition to having no semblance of seasons, so there's no better way to time your unlikely visit, the planet seems to have no plate tectonics. "Earth has many tectonic plates, which are in continuous, albeit slow motion, but it seems like Venus does not have that," Svedhem says. "It is not understood why

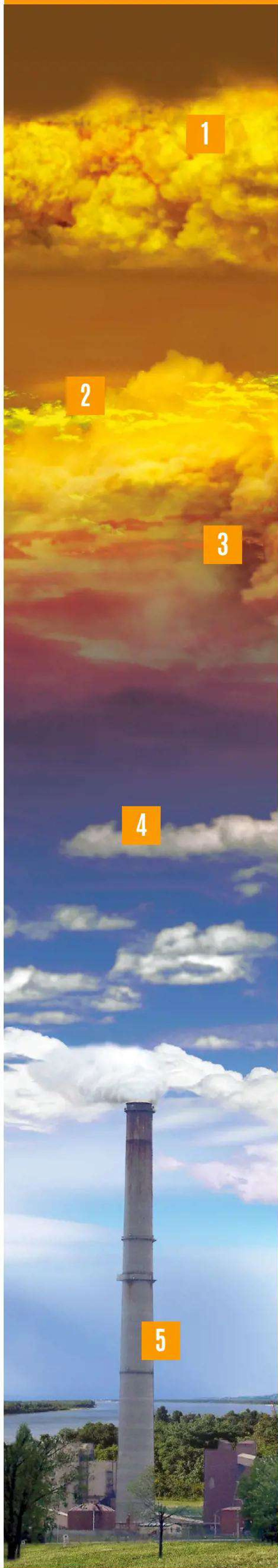


An illustration of Venus as it may have looked in its history before runaway heating

The Russian Venera 9 lander only survived on the surface of Venus for a short time

HOW VENUS' PAST COULD BECOME EARTH'S FUTURE

Could our home planet turn equally barren and inhospitable?



1 Runaway greenhouse effect

Earth would have to warm up considerably to experience a runaway greenhouse effect.

2 Atmospheric thickness

Venus' atmosphere is 96.5 per cent carbon dioxide, while Earth's is 400 parts per million but rising – in part due to human activity.

3 Trapped heat

If Earth's atmosphere gets too thick, it will trap too much heat and cause a runaway greenhouse effect.

4 Solar activity

If humans don't begin the process, then increased solar activity in a few billion years will surely do the trick.

5 Human activity

Some have predicted that human activity and the burning of fossil fuels could begin the runaway greenhouse effect.

> "Venus was likely very similar to Earth after the formation of the Solar System, but it evolved in a very different direction" **Håkan Svedhem**

this is the case." On Earth, plate tectonics give rise to volcanic activity, but the lack of such geological activity hasn't stopped Venus from experiencing volcanism. Radar mapping of the planet has shown that it has over 80,000 volcanoes, far less than the estimated millions of volcanoes on Earth. Of these terrestrial volcanoes, only around 1,500 are estimated to be active. However, the question of active volcanism on Venus is tougher to address. "On Venus, volcanoes were active in the past, and there may still be some volcanic activity today, although we're not yet sure due to the difficulty of observing the surface," Cangi says.

One piece of evidence supporting current volcanism on Venus is its 'youthful' appearance. To consider what this means, compare the surface of the Moon to the surface of our planet. The Moon is almost as old as our planet – 4.53 billion years compared to Earth's age of 4.54 billion years – and both bodies have been subject to the same bombardment of asteroids throughout their history. The surface of the Moon is scarred and pitted with many asteroid impact craters, which can be used to date a planet, moon or large asteroid. Earth, with some notable exceptions, is mostly free of such unsightly cosmic blemishes.

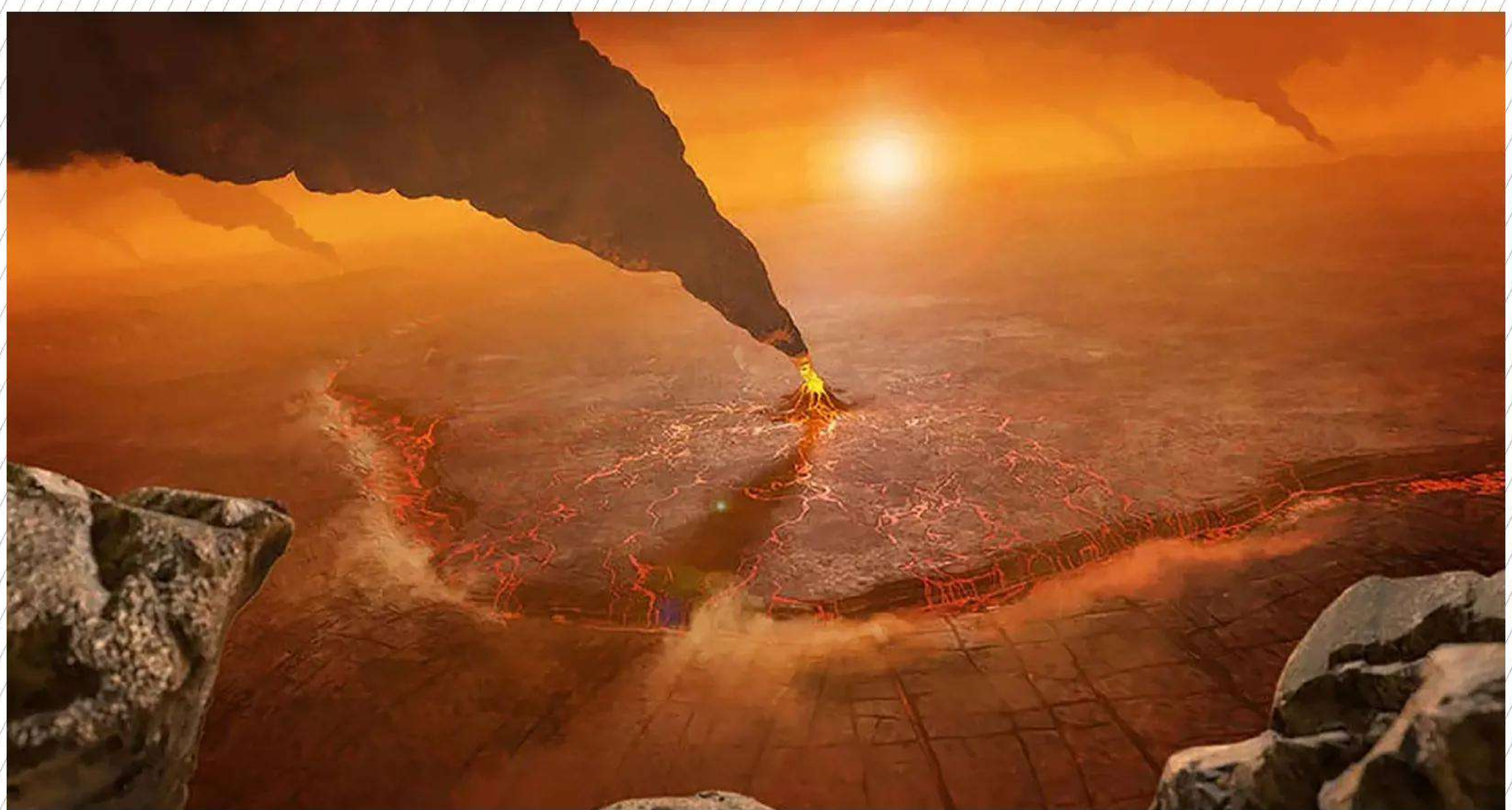
That's because the surface of our planet is constantly being refreshed and recycled on a geological timescale by tectonic plates passing under others and being destroyed, leading to ocean floors being completely replaced over the course of hundreds of millions of years. The Moon lacks this geological recycling, but so does Venus with its single planetary plate. Yet Venus seems to have fewer asteroid impact scars – especially large ones – than expected.

The youthful appearance of Venus could be the result of volcanic activity causing local resurfacing. This could still be happening today at circular patches across its surface called 'coronae' that were first observed by the Magellan spacecraft in the 1990s. These coronae tend to be found in regions of Venus

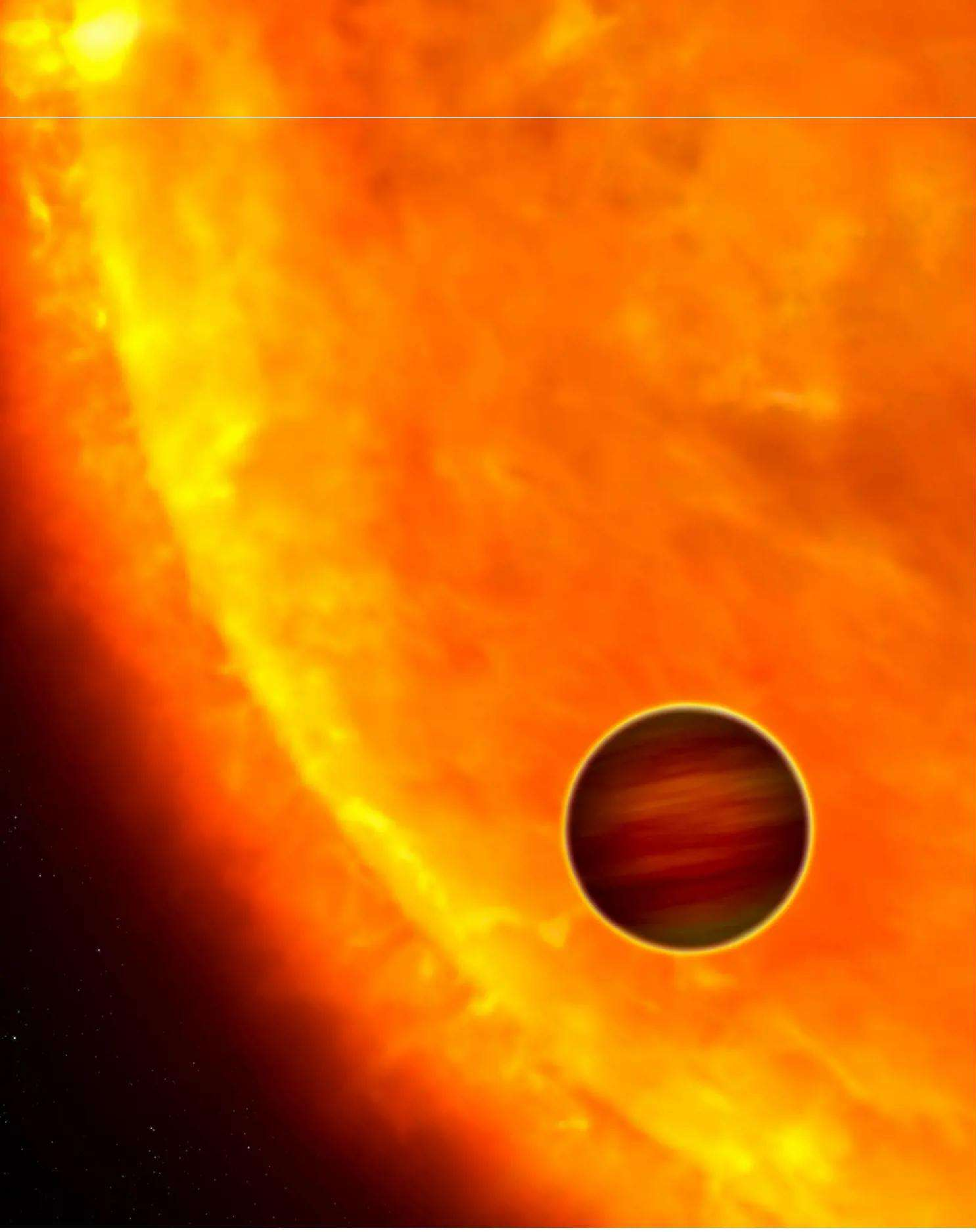
IS VENUS' RUNAWAY GREENHOUSE EFFECT A WARNING TO EARTH?

The 'greenhouse effect' is probably a phrase that's familiar to many of us because Earth is currently experiencing its own greenhouse effect, with global warming as a result. This is mainly driven by the release of greenhouse gases, predominantly carbon dioxide, into the atmosphere as a result of the burning of fossil fuels. However, Earth is unlikely to see a runaway greenhouse effect like that of Venus. But that doesn't mean we can't learn more about Earth's fate if climate change isn't abated by looking at our hellish neighbour. "The process on Earth is very different, and the energy from the Sun at Earth is only about 50 per cent of that at Venus, as Earth is farther away," Svedhem says "But if in some way all the water on Earth could be forced up into the atmosphere, a Venus-like greenhouse effect might happen."

He adds that this is actually certain to happen one day, specifically in around 5 billion years when the Sun has exhausted all of its fuel for nuclear fusion. This will see the outer layers of our star 'puffed out' as the so-called red giant phase begins. "Then all the inner planets will be engulfed by the Sun and will be cooked out," Svedhem says. It's doubtful even this cookout of Earth will see it evolve like Venus for long, however. The swelling red giant Sun is expected to reach Mars' orbit, thus swallowing the closest planet to the star, Mercury, then Venus, Earth and possibly even Mars. "None of this means we shouldn't worry about climate change on Earth," Cangi adds ."Many of the societal and energy system changes that can help mitigate anthropogenic climate change are also good for the health of ourselves, our societies and our economies."



An illustration of potentially volcanic features on Venus called coronae



where its outer rocky layer, called the 'lithosphere', is at its thinnest and most volcanically active. That indicates that despite the lack of plate tectonics, these regions could allow volcanic rock to make its way to the surface, thus refreshing the planet's appearance "The Venus Express mission did find some areas where the surface is very young compared to the surrounding areas, indicating that there has been recent volcanic activity, at least in geological terms, meaning some 100,000 years," Svedhem says. "Some scientists think the planet is completely dead geologically, but this seems not to be the case."

Though we are fairly certain that Venus doesn't have plate tectonics currently, some research suggests that it may have been more like Earth in its past history in this respect. In late 2023, a team of scientists led by Brown University discovered via the collection of atmospheric data the intense surface pressure of Venus, and computer modelling showed that Venus may once have had plate tectonics.

They think that the conditions on Venus would only be possible if the planet had continental plates pushing against and pulling on each other and sliding underneath one another around between 3.5 and 4.5 billion years ago. This contradicts the idea that one of the reasons Earth and Venus have evolved so differently is because Venus only possesses a single continental plate, which

"It takes longer than a Venus year for the planet to rotate once on its axis"

Eryn Cangi

VENUS IN ART AND MYTHOLOGY

The high visibility of Venus in the night sky has made it a fixture in human mythology and art since before history began. In Roman mythology, Venus was the goddess of love, beauty, fertility, prosperity and victory. Considered an ancestor of the Roman people through her son Aeneas, who fled to Italy after the fall of Troy, Venus was the centre of many religious festivals. However, the name 'Venus' was only given to the second planet from the Sun in the 13th century; prior to this, it was known as morgensteorra, or the morning star, and æfensteorra, the evening star in Old English. The term 'morning star' may be more familiar in Latin as 'Lucifer' or the 'light bringer'. In Hebrew the planet was known as 'Helel'.

It's thought that the association between Lucifer and Satan only began around 300 CE when Christian writers Origen, Tertullian, and Augustine of Hippo interpreted the word Lucifer as Satan, or the devil. Before this, notably in the Old Testament of The Bible, the morning star was a metaphor for the arrogance of a Babylonian king, not a proper name for an evil being. This diabolical association in culture has been enforced by literature like Dante Alighieri's *Inferno* and John Milton's *Paradise Lost.* "Venus has a very rich and interesting mythological history, dating thousands of years back in history," Svedhem adds. "This is enabled by the fact that Venus is so bright and anybody can see it, and it moves over the sky fairly fast."

Arguably, the most famous representation of the influence of Venus over the arts is Sandro Botticelli's *The Birth of Venus*, likely painted between 1484 and 1486. Currently displayed in the Uffizi Galleries in Florence, Italy, the painting depicts the goddess Venus arriving at the shore after her birth. The beauty of *The Birth of Venus* is starkly different from its turbulent and hellish planetary namesake.

acted as a 'stagnant lid'. This would have prevented gas from leaking from the interior of Venus to its atmosphere, and the team theorises that this stagnant lid would make the rich carbon dioxide and nitrogen composition of elements in the Venusian atmosphere seen today impossible.

Scientists have speculated that plate tectonics on≈Earth played a role in the emergence of life on our planet by allowing heat to escape the interior of Earth, and by generating a magnetic field that protects life on our planet from the bombardment of charged particles from the Sun. That means if Venus once had plate tectonics, there's a chance it once supported the emergence of simple microbial life.

When it comes to the question of Venus supporting life at its surface, it doesn't matter one bit that it's in the so-called 'habitable zone' of the Solar System; the answer is a hard no. But there's a caveat there – what about life in the clouds? Other researchers believe that Venus may still have the right stuff needed for life, albeit very different from life found on Earth, in its upper atmosphere. Clearly, the atmospheric conditions of Venus at its surface aren't going to be conducive to a holiday stay, and humans aren't going to prosper in an atmosphere of 96.5 per cent carbon dioxide and 3.5 per cent nitrogen, but what about conditions in the upper atmosphere, where there isn't as much pressure.

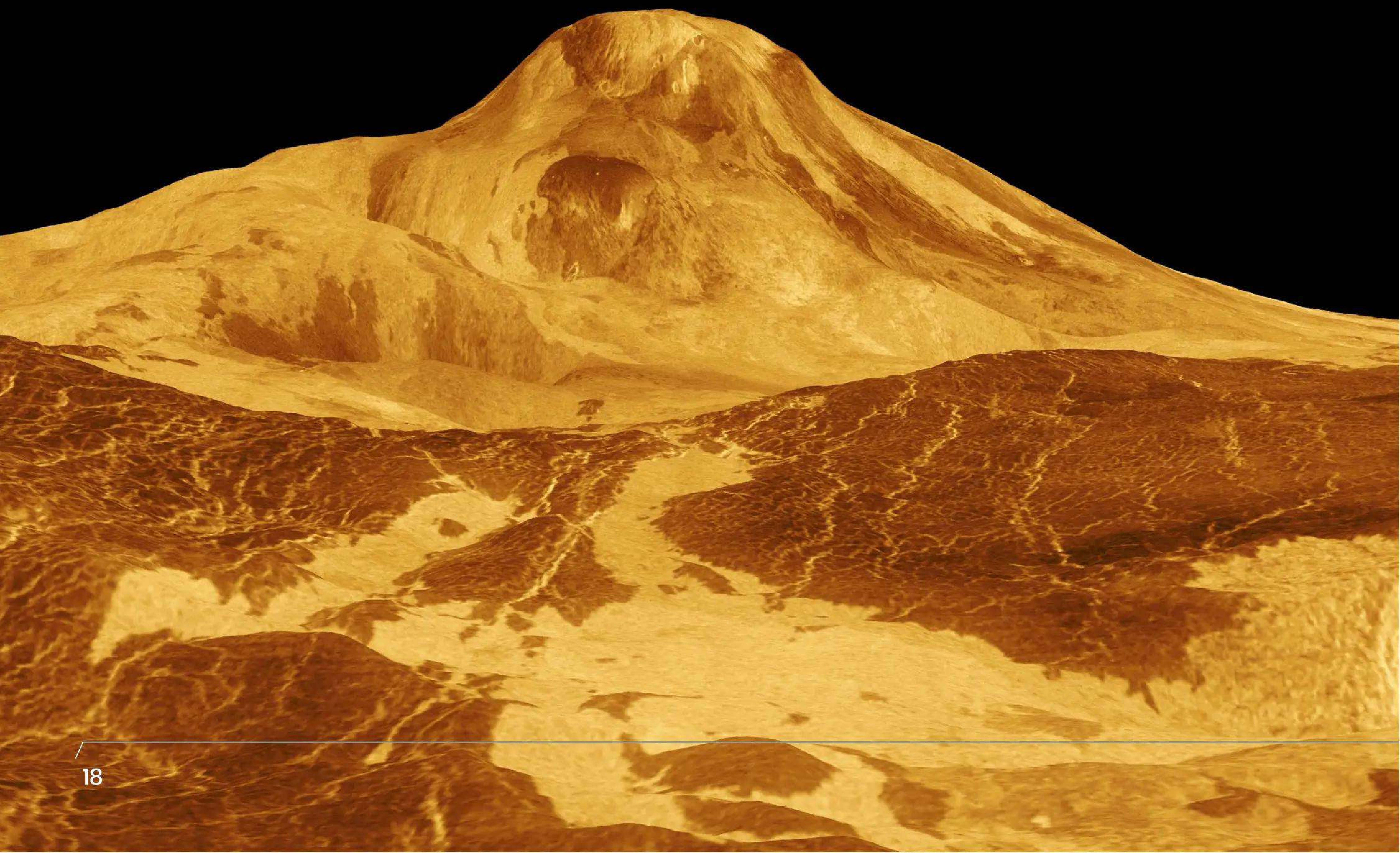
Though the pressure is lower in the upper Venusian atmosphere, while there you'd have to contend with the clouds of Venus, which are so dense that they have helped the planet's surface remain mysterious even to the occupants of its nearest planetary neighbours. If you're picturing soft, fluffy clouds of water vapour, think again. The thick yellow clouds of Venus are mostly composed of potent sulphuric acid, and they blanket the entire planet. Yet as inhospitable as this sounds to us, many scientists think that these Venusian clouds could actually support life. In September 2020, Cardiff University researcher Jane Greaves and her team reported the detection of phosphine in Venus' clouds. Three years later, the same team found traces of the same chemical even deeper in Venus' atmosphere using the James Clerk Maxwell Telescope in Hawaii and the Atacama Large Millimeter/submillimeter Array (ALMA) in Chile.

"We've seen a gas called phosphine that on Earth is mainly made by microbes. However, it could have a non-life source on Venus, which is hard to rule out until we know more about the planet's geology and atmosphere," Greaves tells **All About Space**.

"We've seen a gas called phosphine that on Earth is mainly made by microbes. However, it could have a non-life source on Venus"

Jane Greaves

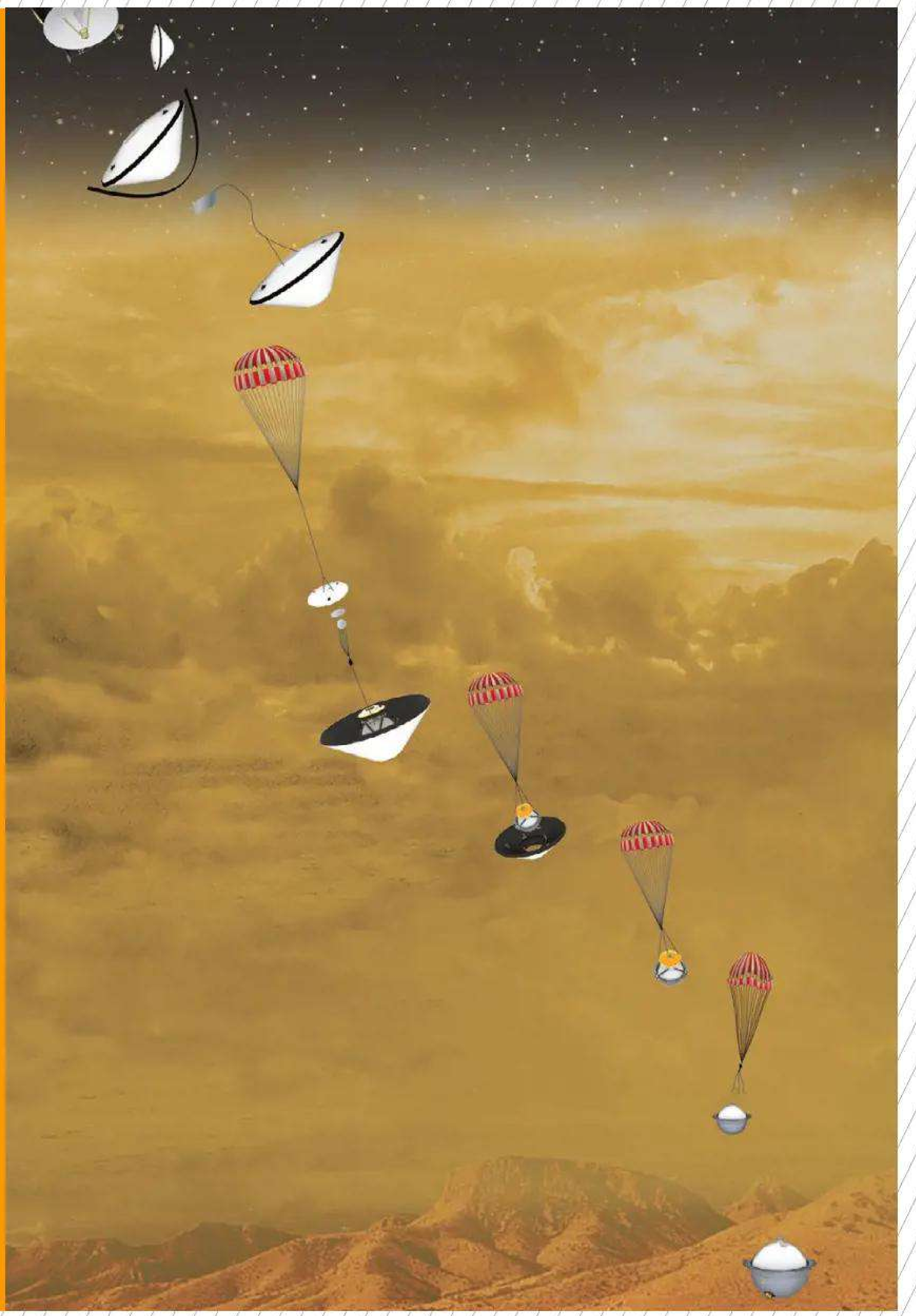
The highest volcano on Venus is Maat Mons



THE DAVINCI PROBE:
GETTING THE DROP ON VENUS

Set to launch in 2032, the Deep Atmosphere of Venus Investigation of Noble gases, Chemistry and Imaging (DAVINCI) mission will investigate the origin, evolution and present state of Venus in unprecedented detail. What will really set this mission apart from previous investigations, however, is the fact that in addition to studying the cloud tops of Venus, DAVINCI will drop a probe to the surface of the planet. This titanium atmospheric probe will have its descent slowed by a parachute, allowing its five scientific instruments to study the clouds of Venus and the layers of its atmosphere. About 30 minutes into the hour-long descent, the probe will reach a region of the planet's atmosphere 90 times denser than the atmosphere of Earth, so dense it will be naturally buoyed, meaning it can jettison its parachute.

Though DAVINCI's probe is designed to withstand the sulphuric clouds of Venus, with the immense atmospheric pressure of the planet and its hellish temperatures, it probably won't survive its landing. If it does, the probe could give scientists an unprecedented look at the surface of our tumultuous neighbour, albeit for just 17 minutes. "DAVINCI will land on the surface and measure many parameters of the atmosphere during the descent, especially noble gases and isotopic ratios for several gases," Svedhem says. "This will tell us much about the evolution and history of the planet."



Astronomers looking at rocky planets around other stars have previously suspected that if this pungent gas, which is poisonous to humans, was detected in the atmosphere of such a world, it could only be produced by a life form. "It seems just possible life could exist on Venus if life is very robust to changes and extreme conditions, and if there was an origin of life on Venus," Greaves says. "There may be showstoppers, however, such as the low levels of liquid water, unless life is very agile in finding and preserving water."

The announcement of phosphine in the atmosphere of Venus has sparked a heated debate and a surge of follow-up studies in the astronomical community. These follow-ups have generally failed to spot the intriguing molecule in the Venusian atmosphere, meaning that there is a lot more research to be done before anyone is comfortable suggesting Venus is occupied by even the simplest life.

Clearly, if this potential biosignature in Venus' atmosphere is confirmed and is coming from a life form at or near its surface – and this is a huge if – it is an exotic form of life with hardiness way beyond even the most hardy 'extremophiles' of Earth, such as tardigrades. Alternatively, Venus' life may be aerial in nature, existing in the dense clouds of the planet buffeted by its violent winds. "I've always been thrilled by the idea that life extends beyond more than just Earth and could take very different forms to what we know here, and I love how easy it is to observe Venus each time it swings past us - the alien planet next door!" Greaves says.

Let's face the fact that even if Earth's evil twin could support a strange form of life in its clouds, a Venus vacation is off. Nevertheless, planetary scientists will continue to be fascinated by Earth's evil twin. "I'm interested in anything we don't understand, so other planets are perfect. Venus is especially fascinating because there's still so much we don't know," Cangi concludes. "I'm very interested in what makes planets habitable and how that can change over time, so Venus is a great case study and example of a planet that could have once been habitable but isn't today."

Robert Lea
Space science writer
Rob is a science writer with a degree in physics and astronomy. He specialises in physics, astronomy, astrophysics and quantum physics.

FOCUS ON

APOPHIS WILL COME TO EARTH IN 2029, AND IT COULD MEET SOME TINY SPACECRAFT

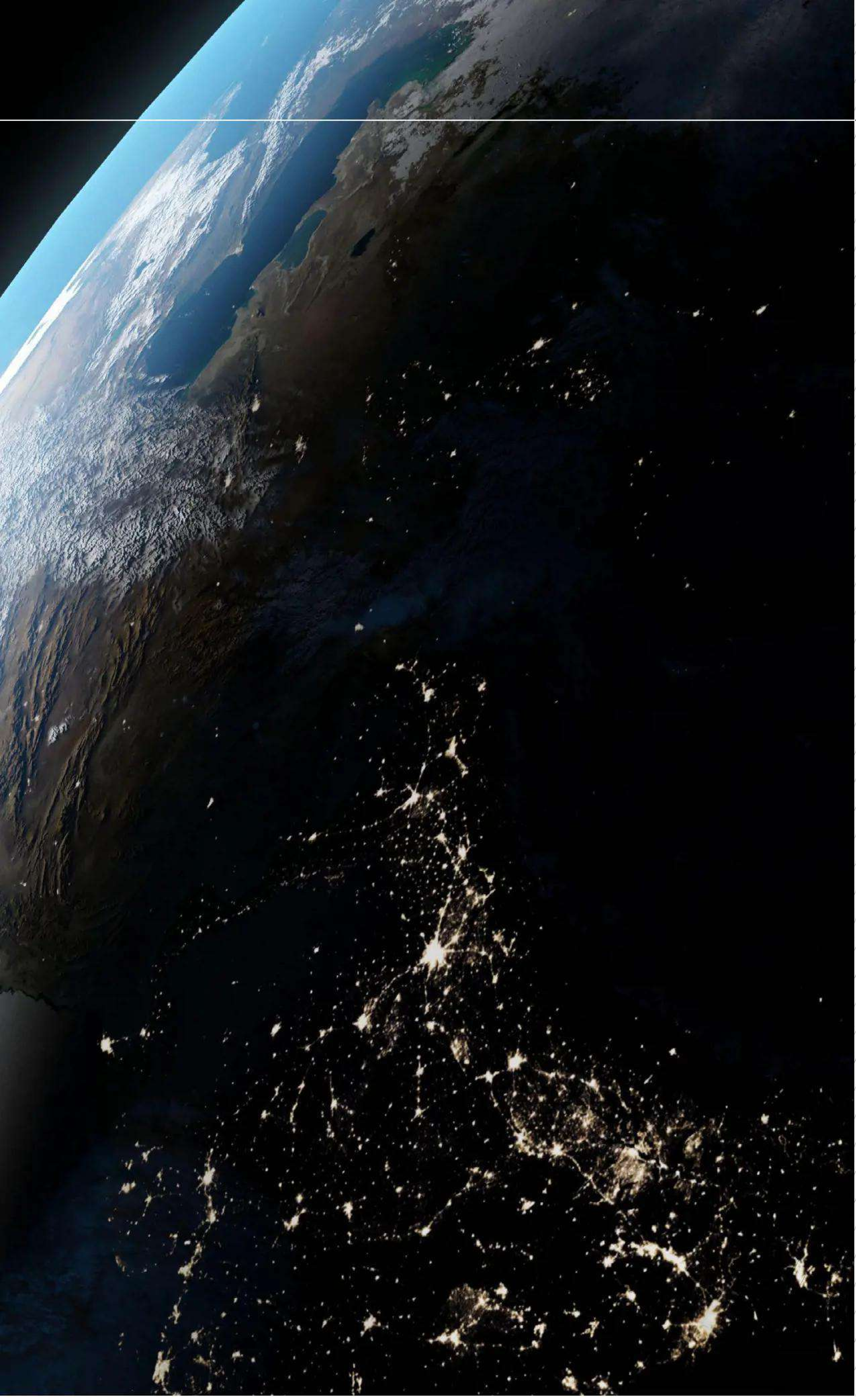
Scientists have unveiled three concepts for tiny spacecraft that could voyage from Earth to meet the asteroid in April 2029

Reported by Robert Lea

In just under half a decade, a 305-metre (1,000-foot) wide asteroid named after the Egyptian god of chaos and destruction, Apophis, will pass within 48,300 kilometres (30,000 miles) of Earth. Scientists don't intend to allow the rare close passage of a space rock of this size to go to waste. On 13 April 2029 – a Friday, no less – when Apophis makes its closest approach to Earth, it will become so prominent over our planet that it will be visible with the unaided eye. NASA's OSIRIS-APEX will be on hand to meet the near-Earth asteroid (NEA) personally. But if things shape up, that NASA mission could be joined by a host of little satellites during its rendezvous.

Under the auspicious 'NEAlight' project, a team from Julius-Maximilians-Universität Würzburg (JMU) led by space engineer Hakan Kayal has revealed three concepts for such spacecraft. Each of the proposed satellites will aim to exploit this asteroid passage because Earth experiences just one such event every millennium. The goal? To collect data that could help scientists better understand the Solar System, and perhaps even aid in the development of defence measures against dangerous asteroids.

As to why Apophis is an apt target for a planetary defence study? Discovered in 2004, the asteroid quickly rose to the top of tables that measure the risk of so-called potentially hazardous asteroids (PHAs), or asteroids with widths of 140 metres (460 feet) or more that come within 20 lunar distances of Earth. Both the size of Apophis and how close to Earth its trajectory



"The team's first concept is a small satellite that will join Apophis for a period of two months"

brings it saw the asteroid remain at the top of both the European Space Agency's (ESA) 'impact risk list' of PHAs and NASA's Sentry Risk Table for 17 years. That was until a close flyby of the asteroid – a space rock that is almost as wide as the Empire State Building is tall – in March 2021 allowed NASA scientists to determine Apophis actually won't hit Earth for at least 100 years.

Though we now know Apophis won't collide with Earth in the next century, its scientific impact in 2029 will still be tremendous, and space agencies from countries across the globe will be closely tracking its trajectory. As an asteroid that formed around the same time as the planets from leftover material around the infant Sun, Apophis also offers researchers a unique opportunity to determine what the Solar System's chemical composition was around 4.6 billion years ago.

Despite the fact we're aware of around 1.3 million asteroids in the Solar System, of which 2,500 are considered potentially hazardous, spacecraft missions to study asteroids are relatively rare. Thus far, only 20 missions have been deployed to study asteroids in situ, including OSIRIS-REx, Japan's Hayabusa and Hayabusa2 craft, the ESA's Rosetta space probe and the asteroid-hopping NASA mission Lucy, currently journeying to the trojan asteroids that share their orbit with Jupiter. The JMU team must carefully consider its options when considering a future asteroid-investigating spacecraft.

The team's first concept is a small satellite that will join Apophis for two months as it makes its close approach to Earth in April 2029. The craft will stick with the 'god of destruction' space rock for weeks after, even as it moves away. Over the course of the mission, this German national spacecraft will photograph Apophis and make measurements documenting any changes the NEA undergoes during its flyby. This particular mission would be a challenging one because of its duration, the distance it will be required to travel and the fact that the craft will have to function autonomously for long periods. It would also have to launch at least a year before Apophis arrives in Earth's vicinity.

The team's second concept involves integration with a larger spacecraft that's being planned by the ESA called RAMSES. This mission will be outfitted with smaller satellites, measuring equipment and telescopes. RAMSES, named after Egyptian pharaoh Ramesses the Great, would journey to Apophis and stay with the asteroid as it passes Earth. If the second concept reaches fruition, one of the small satellites carried by RAMSES will be designed by the JMU team, with this project requiring less technical effort than the first concept while promising to reap greater scientific knowledge.

The third concept involves a small satellite that will only briefly fly past Apophis when the asteroid is at its absolute closest to Earth, snapping images of the asteroid in the process. This concept would require much less effort, and the craft would be relatively inexpensive. The downside of concept three, however, is that its observation time would be limited, which would also limit the volume of knowledge this mission would add to our understanding of asteroids. On the plus side, the small-scale mission could launch just two days before Apophis arrives. Also, if concept three were to successfully observe Apophis, it would demonstrate the capability of small and inexpensive satellites in studying asteroids, perhaps leading to an increased interest for in-situ asteroid-studying missions.

MYSTERIES OF THE UNIVERSE

HOW IS WATER FORMING ON THE MOON?

Scientists have made a breakthrough discovery to explain the origin of water ice. Could water on the lunar surface be forming due to high-energy electrons from Earth?

Reported by David Crookes

For decades, scientists have suspected that water ice exists on Earth's Moon. Water is also known to be widely distributed – not just present in the permanently shadowed areas of our natural satellite, but in the sunlit parts too, as confirmed by NASA's Stratospheric Observatory for Infrared Astronomy (SOFIA) in 2020, which noted molecular water trapped in regolith grains. Granted, the amount of water is small – there's actually 100 times more water in the Sahara Desert than in lunar soil. But that doesn't make its presence any less significant. The fact it's there at all is important enough.

The big question is how it came to be there. Could the water have been carried by comets and asteroids? Was it shared by Earth? Scientists have spent years trying to figure out this mystery, but now it seems as if they could be closer than ever. Shaui Li is a planetary scientist at the University of Hawaii at Mānoa. He became interested in working out where water on the Moon could have come from when he was in graduate school in 2011. This was at a time when data from the Moon Mineralogy Mapper imaging spectrometer on board India's first mission to the Moon, Chandrayaan-1, was well-calibrated and available.

"Whether and how much water exists on the lunar surface and where it has come from is a question that has been asked many times over in the lunar community," he tells **All About Space**. "The debate continued even after the return of Apollo lunar samples because most of them were exposed to the atmosphere, which led scientists to suspect that the observed water in the Apollo samples was sourced from Earth. At the time I started graduate school, the Moon Mineralogy Mapper data was just available, and that dataset was the only one scientists could use to study lunar surface water." It's this information, gathered between 2008 and 2009, which has been leading Li to an exciting theory, because it includes data collected when the Moon traversed through Earth's magnetotail – an area which, he says, effectively forms a natural laboratory for studying the formation processes of lunar surface water.

Finding water ice on the Moon is extremely challenging, which is why direct detection of surface water ice was only successful a few years ago. Li was

The Polar Resources Ice Mining Experiment-1 is an attempt by NASA to look for water ice on the Moon close to Shackleton crater

WATER ON THE MOON

TWO
The two poles of the Moon have permanently shadowed regions

600
There's more than 600 billion kilograms of water ice at the poles

1645
The presence of water on the Moon has been hypothesised for many centuries

2009
India's first lunar mission found water on the Moon

100
The Moon is 100 times drier than the Sahara Desert

2013
In 2013, water was found in samples from Apollo 15, 16 and 17

Trillions
Scientists believe trillions of pounds of water is trapped in tiny glass beads

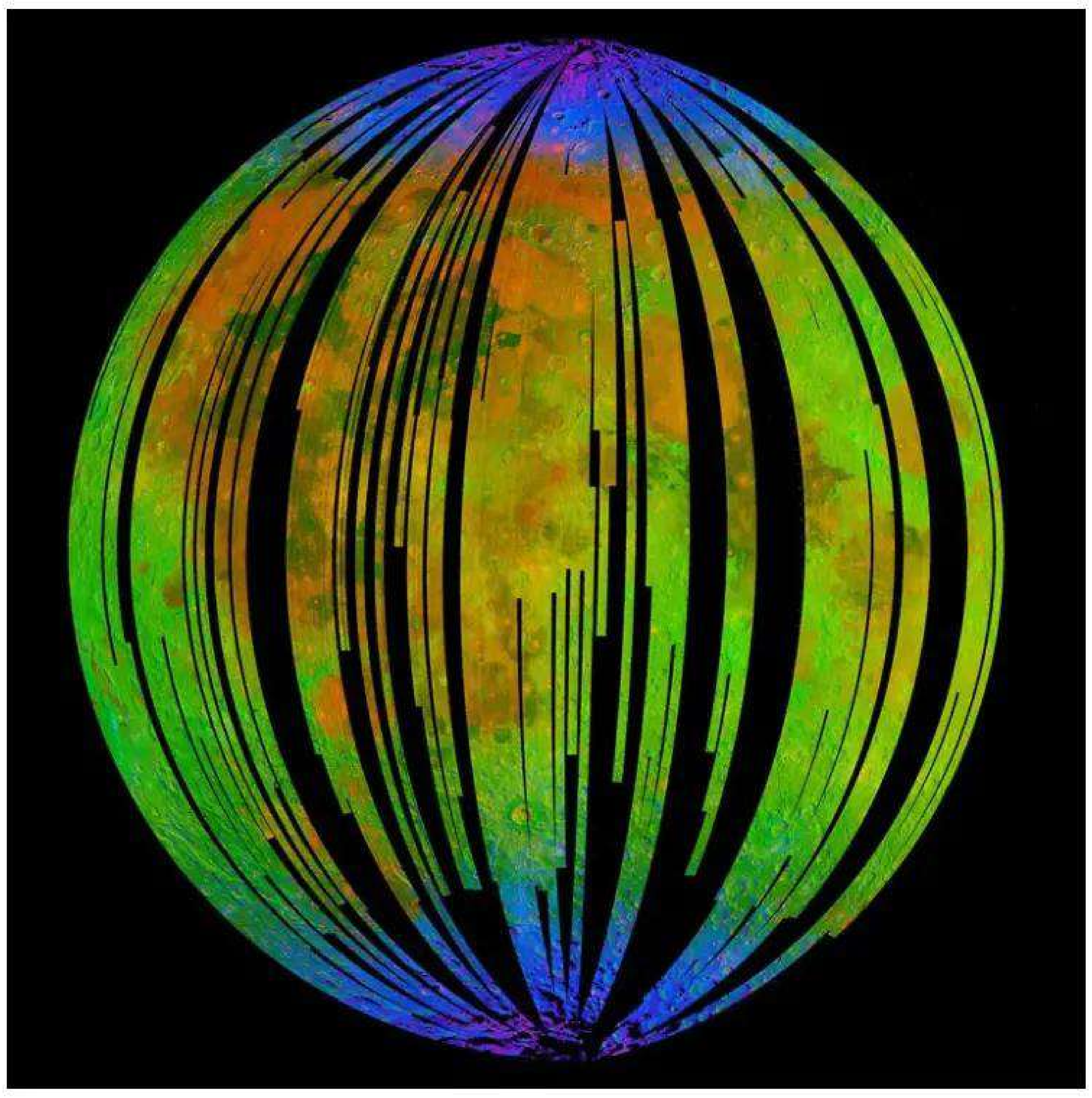
2023
The first map of Moon water was completed in 2023

at the forefront of this particular discovery in 2018, leading a study which found surface-exposed water ice in the lunar polar regions, as well as an abundance and distribution distinct from other airless bodies in the inner Solar System such as Mercury and Ceres.

"There have been a few challenges," Li explains. "First and foremost is that the water ice content on the lunar surface and shallow subsurface is extremely low. So while radar is a powerful tool for detecting water ice on many planetary bodies, such as Mercury, when the water ice content is low, the dielectric constants of the ice regolith mixtures cannot be significantly modified, and thus it cannot show anomalous signals in the radar data." As such, a lot of studies have sought indirect ways to detect water ice. "For instance, the neutron technique can detect any hydrogen-bearing species, including water ice," Li continues. "But when we see strong neutron data anomalies, it's difficult for us to tell whether they are water ice or hydroxide-bearing materials, dihydrogen or even hydrogen."

The hunt for water ice has been made all the more difficult because it's hard to clearly see and analyse certain parts of the Moon. "Near-infrared reflectance spectroscopy is currently the most efficient and direct way to detect low contents of water ice, but it's super challenging to use in the permanently shaded regions on the Moon where water ice is possibly harboured the most," Li adds. "This is because reflectance spectroscopy relies on sunlight as the light source and there's no direct sunlight in the permanently shaded regions. Since there's no atmosphere on the Moon, the scattered light from rough topography is the only light source to the permanently shaded regions, and it's super weak – less than one per cent than the sunlit surface."

Add a low water ice content to the mix and you can see why it's been extremely difficult to detect water using remote-sensing technologies. "It has been impossible to tell its origins before definitive detections of water ice," Li affirms. And that's why this mystery has been taking so long to resolve. To reach a conclusion, Li has been on something of an academic journey, making breakthroughs many times over. In 2020 he led a study which discovered the oxidised iron mineral

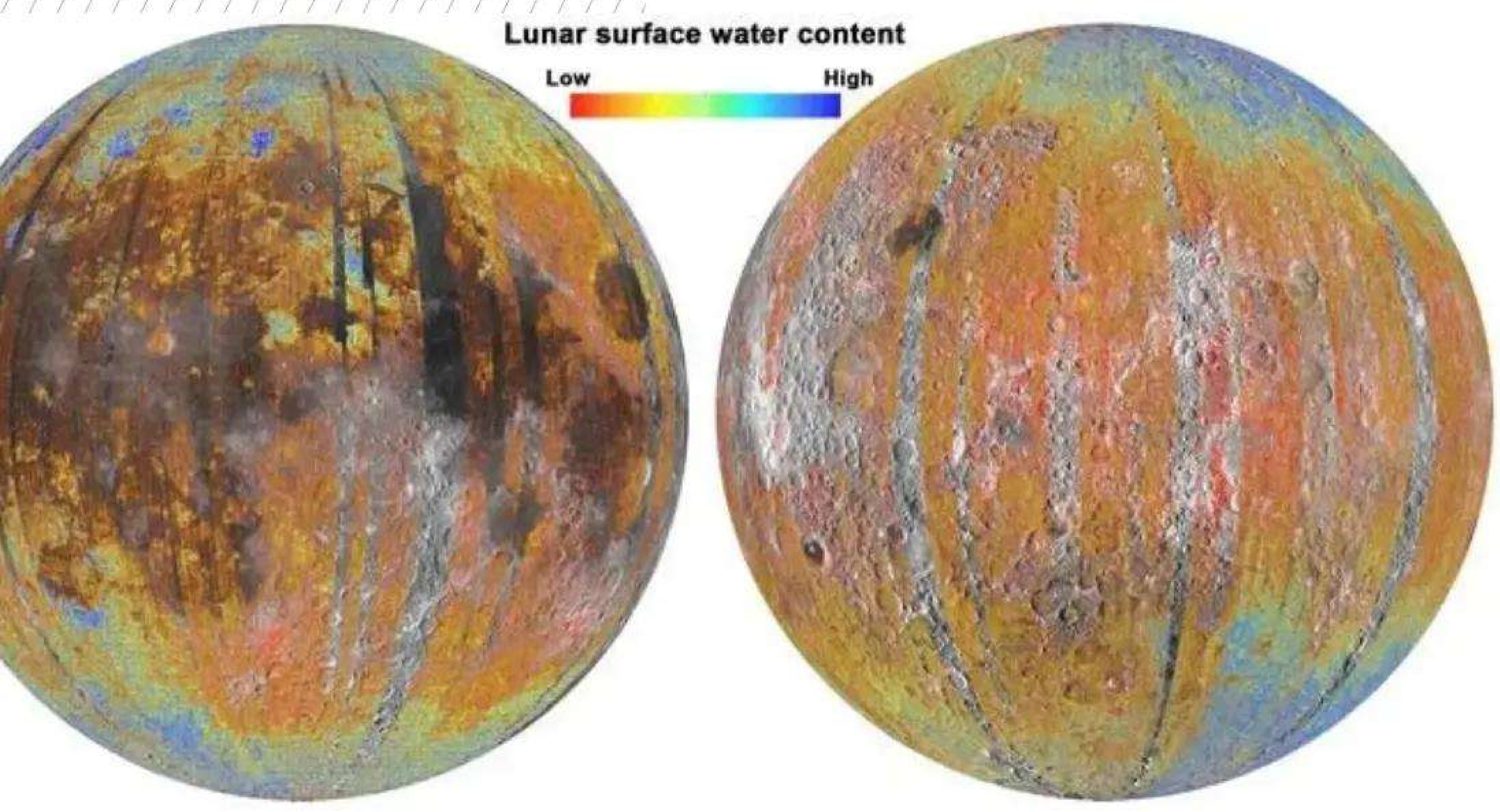


hematite at high latitudes on the Moon. Since the Moon is virtually devoid of oxygen, this was unexpected.

This has led Li to believe that lunar surface iron is being oxidated by oxygen from Earth's upper atmosphere travelling via the magnetotail. Such weathering then led Li to investigate the Moon's passing through this area in much more detail. To better explain, the magnetotail is an elongated part of the magnetic bubble which surrounds our planet, shielding it from high-energy particles delivered from the Sun in the solar wind while allowing the Sun's light photons to pass. The magnetotail extends beyond the orbit of the Moon, and the celestial body orbits through it once every month.

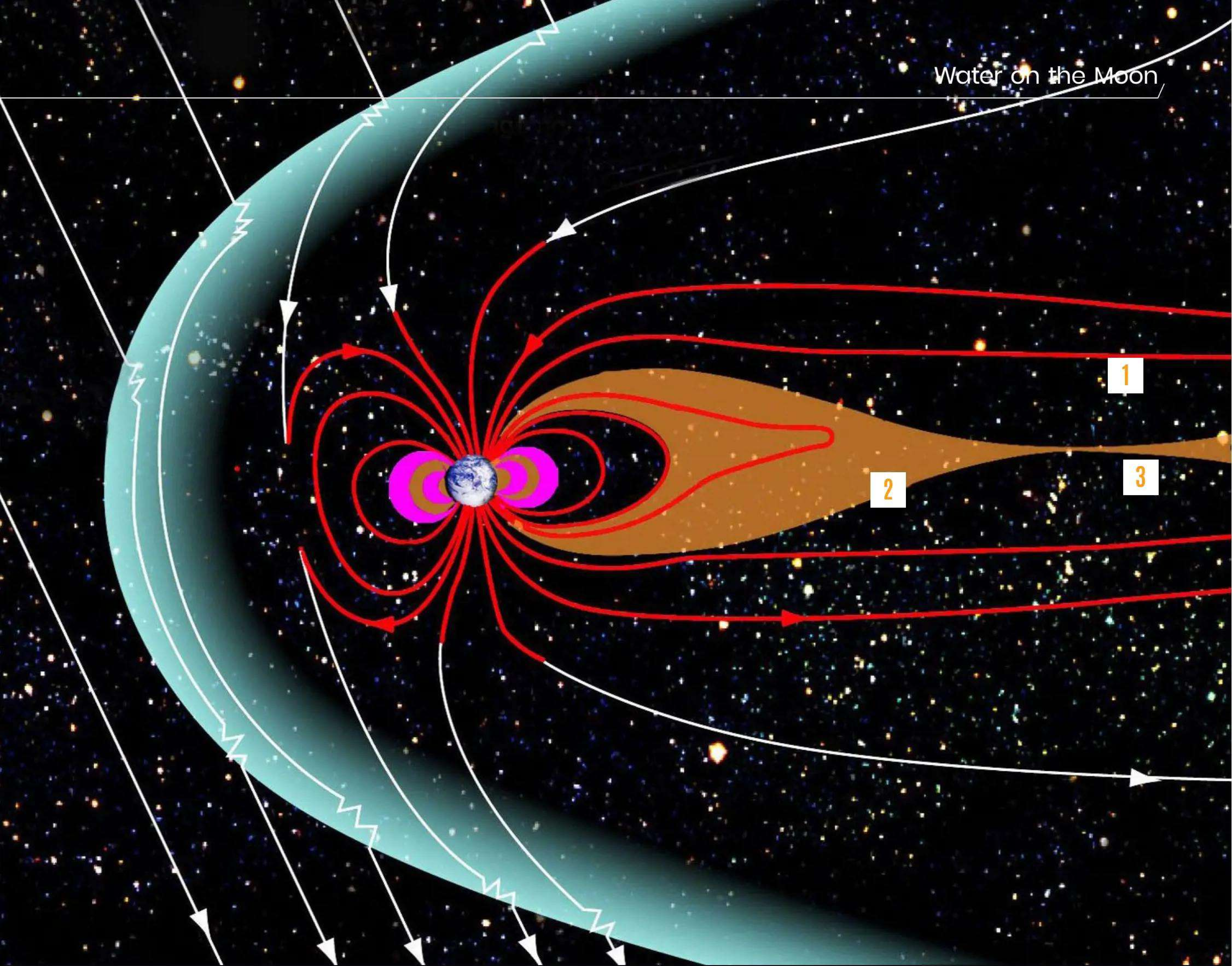
With no solar wind in the magnetotail, there are no solar wind protons, although there are high-energy electrons and ions forming a plasma sheet. In theory, a lack of solar wind should have meant no water could be formed whenever the Moon was within the magnetotail. But as Li discovered, that was not the case. Water formation on the lunar surface was almost identical regardless of whether the Moon was inside or outside Earth's magnetotail. "I was surprised and double-checked it several times," Li says. "Then I realised that there should be some unrecognised processes about water formation on the Moon when the solar wind is shut off."

It suggests that the solar wind cannot be the only explanation for the presence of water on the Moon – a twist in the tale which has been getting scientists very excited. "Our understanding about the origin of lunar surface water has been drastically improved in the last decade through remote-sensing observations, laboratory simulations of solar wind radiation and



The Moon Mineralogy Mapper confirmed water locked in minerals on the Moon, shown here in blue

This shows how water is distributed on the near and far side of the Moon



HOW THE MOON ENCOUNTERS EARTH'S MAGNETOTAIL

The Moon travels right through this part of our planet's magnetosphere

1 Creating the magnetotail

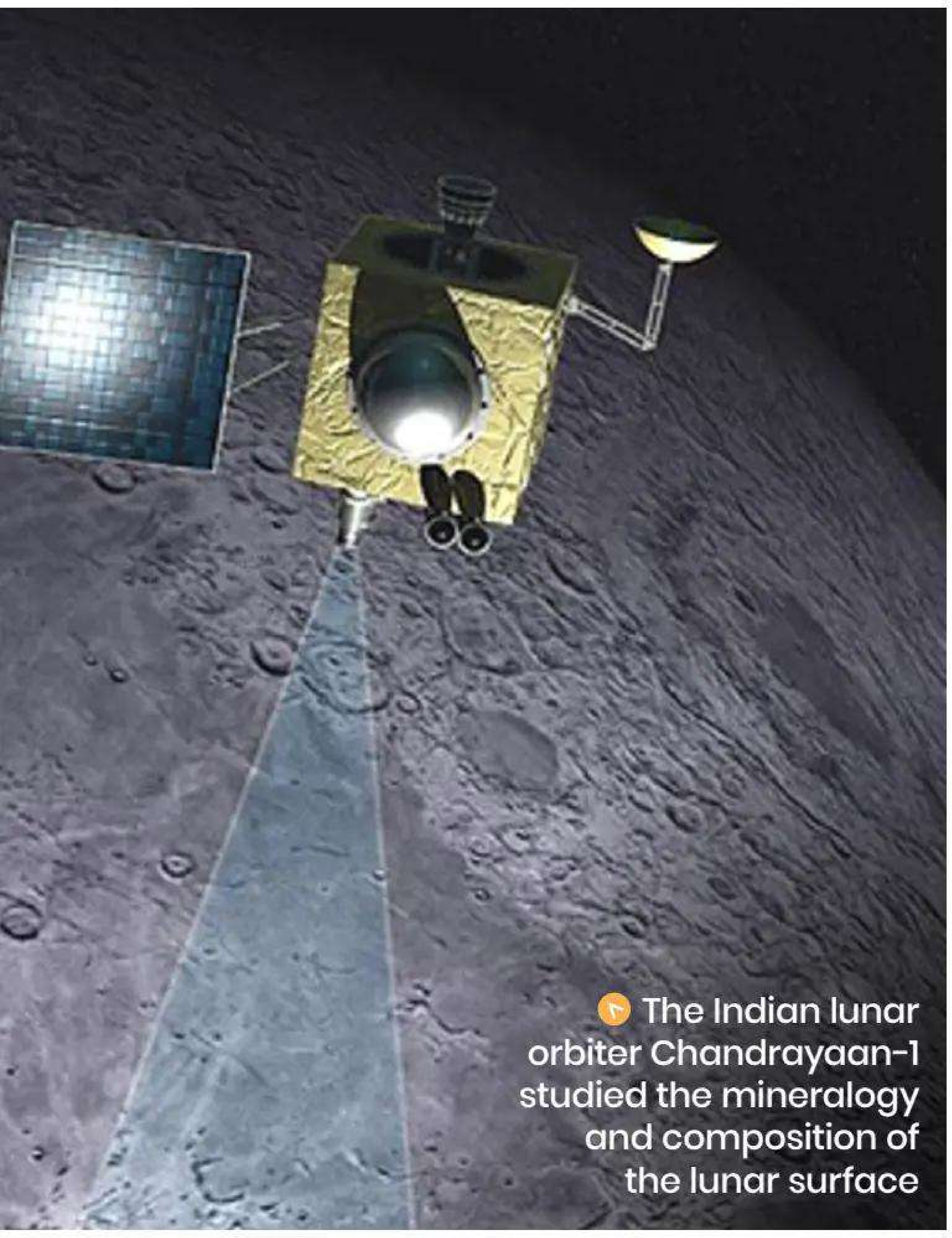
The magnetosphere is an area around our planet that is dominated by its magnetic field. It protects Earth from harmful levels of radiation from the Sun. When the solar wind collides with the magnetosphere, it's deflected around the planet. This forms a lengthy tail.

2 The plasma sheet

Trapped inside the magnetotail, which is about 1,000 times Earth's radius, is the plasma sheet. It contains hot charged particles, including electrons. There are almost no solar wind protons inside the magnetotail.

3 Orbiting Moon

The Moon travels through the magnetotail and its plasma sheet. At this stage, it's protected from the solar wind. Since water is still formed on the lunar surface within the magnetotail, it points to the possibility of new sources of water or formation processes.



The Indian lunar orbiter Chandrayaan-1 studied the mineralogy and composition of the lunar surface

WHERE DID THE MOON GET ITS WATER FROM?

There are a number of theories explaining the presence of water on the Moon

Water was transported by comets

Scientists already believe that much of the water on Earth was carried by comets and asteroids colliding with the planet's surface. The same could also be true of the Moon – and the two bodies may even have received water at the same time. The Moon could have been a water-strewn chunk of Earth that broke away billions of years ago.

Water is produced by the solar wind

Small amounts of water can be found outside of the polar regions, and the Sun may be playing a big part in this. Oxygen atoms are bound in rocks and particles on the surface of the Moon, and their chemical bonds may be broken by the solar wind, which carries hydrogen. Two hydrogen atoms and a single oxygen atom create water.

Electrons play a part

The latest study by the University of Hawaii at Mānoa has found that water forms even when the Moon is protected from solar wind photons at the point when the Moon passes through the Earth's magnetotail. This points to the potential for high-energy electrons in a plasma sheet within the magnetotail playing a part in water formation on the lunar surface.

theoretical modelling," Li explains. "The community believes that implantation of solar wind protons should be one of the major processes inducing water on the lunar surface.

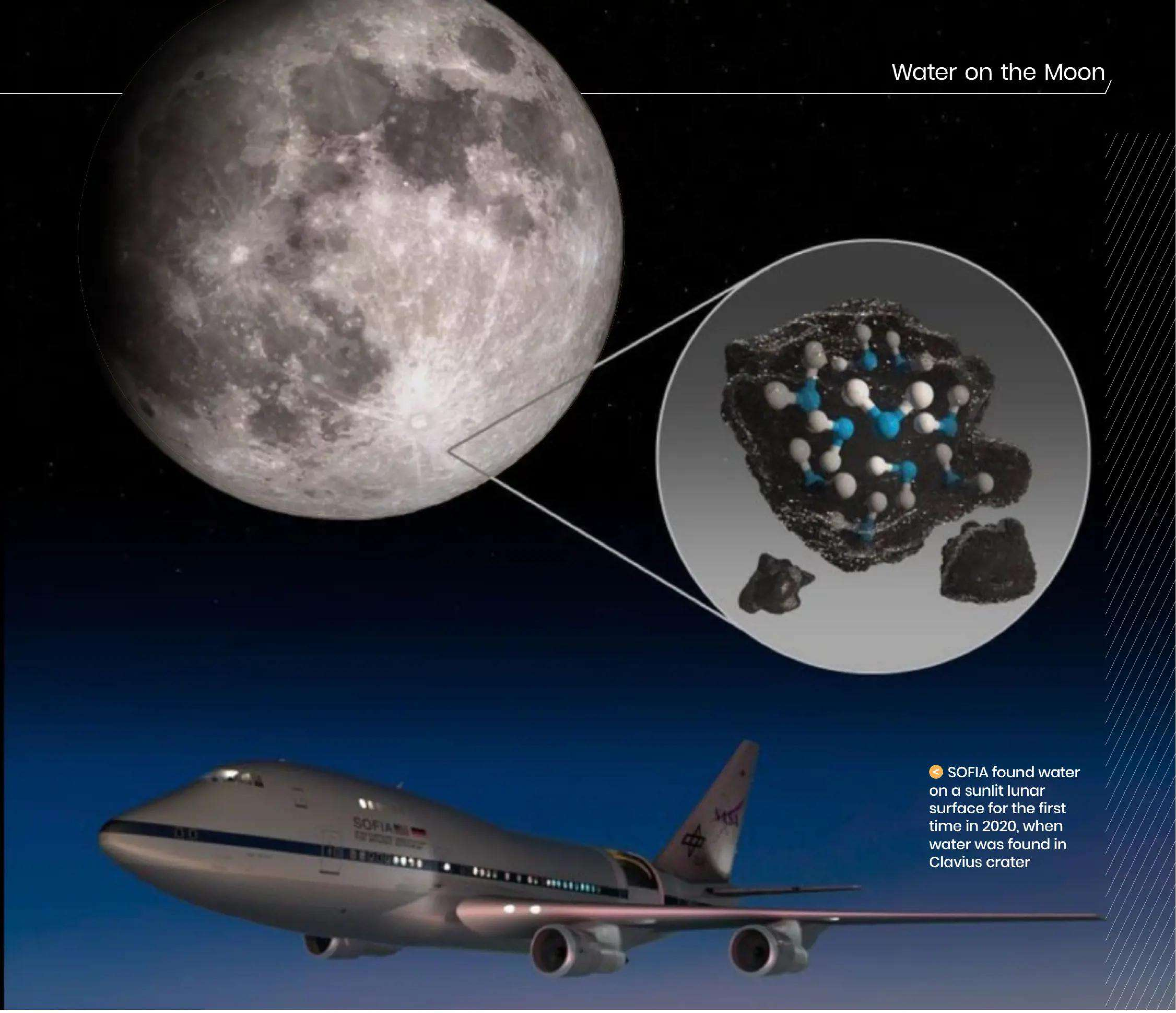
"The Moon's passage through Earth's magnetotail drew my attention after I made the first global water map of the Moon in 2017 because it's well known, and has been measured, that solar wind protons can be almost completely shielded in the magnetotail. If implantation of solar wind protons is a major process inducing water on the lunar surface, it's predicted there's no water formation in the magnetotail due to the shielding of solar wind protons. After I formulated this hypothesis, I started to process the data, and I expected to see no water formation in the magnetotail. When I saw the data analysis results showing no water content change in the magnetotail, I was totally surprised. There must be unrecognised processes going on that are different from a typical implantation of solar wind protons."

Working out what those processes could be quickly occupied Li's mind. The high-energy electrons within the plasma sheet that resides within the magnetosphere through which the Moon travels could, Li surmised, not only be contributing to the weathering processes on the lunar surface, but aiding the formation of water, too. "Our theory about lunar surface water formation by solar wind implantation predicts no water formation in the magnetotail," Li affirms. "However, the remote-sensing observation shows a similar water formation rate in the magnetotail which is completely contradictory to the hypothesis. Then I realised that there should be unrecognised processes about water formation in the magnetotail not due to the implantation of solar wind protons."

All of this points to the water on the Moon being very closely tied to Earth. "The solar wind protons do not directly help water formation in the magnetotail," Li affirms. But that isn't to say that the solar wind isn't having any effect at all. "We believe that the hydrogen source in the water formation process in the magnetotail should be from solar wind," Li says. "Earth's magnetic field is the force that is accelerating electrons in the plasma sheet, and we know the plasma sheet connects to Earth. But the sources of electrons in the plasma sheet are not completely clear. Studies suggest that electrons could be from both Earth and solar wind."

Such findings are significant. It explains how water ice can gather on the surface in permanently shaded regions, and the information will be useful for future crewed missions to the Moon, shedding light on where water ice can be concentrated and distributed. "It may help explain the surface

Shackleton crater is in a permanently shadowed region of the Moon



SOFIA found water on a sunlit lunar surface for the first time in 2020, when water was found in Clavius crater

water ice observed in the permanently shaded regions where sunlight cannot directly reach; these are regions where the high-energy electrons in the plasma sheet can reach," affirms Li. "Electrons also travel in random directions in the plasma sheet, and the plasma sheet is much bigger than the Moon."

The next step is to track the Moon as it travels through to the magnetotail so that the team can investigate the plasma environment and water content at the lunar poles during the passage – something Li is going to be doing as part of NASA's Artemis program. "We will need ground observations of the plasma environment and the water content variation both on the sunlit surface on the lunar nearside and in permanently shadowed craters on both the near and far side," Li says.

This could also help explain how water could be present on other celestial bodies, and that in turn could also assist in the wider hunt for life. "High-energy electrons from a solar storm can reach all airless body surfaces in the Solar System, which means that they can contribute to water formation," Li explains. "And this not only applies to the Solar System, but also applies to the universe, where water can be formed by high-energy electrons in conjunction with protons and oxygen-bearing materials."

As such, the team's research, which was published in the journal *Nature Astronomy*, could prove pivotal, showing how water is distributed throughout our Solar System. With crews set to visit the Moon aboard Artemis III in 2025, it's also rather well-timed. Learning more about water on the Moon could eventually pave the way for many more discoveries in the wider Solar System and beyond.

David Crookes

Science and technology journalist

David has been reporting on space, science and technology for many years, has contributed to many books and is a producer for BBC Radio 5 Live.

FOCUS ON

LONG AGO, A LAKE ON MARS MAY HAVE BEEN SPRAWLING WITH MICROBES

Curiosity discovered manganese oxide in bedrock in a Martian region that may have been a shoreline billions of years ago

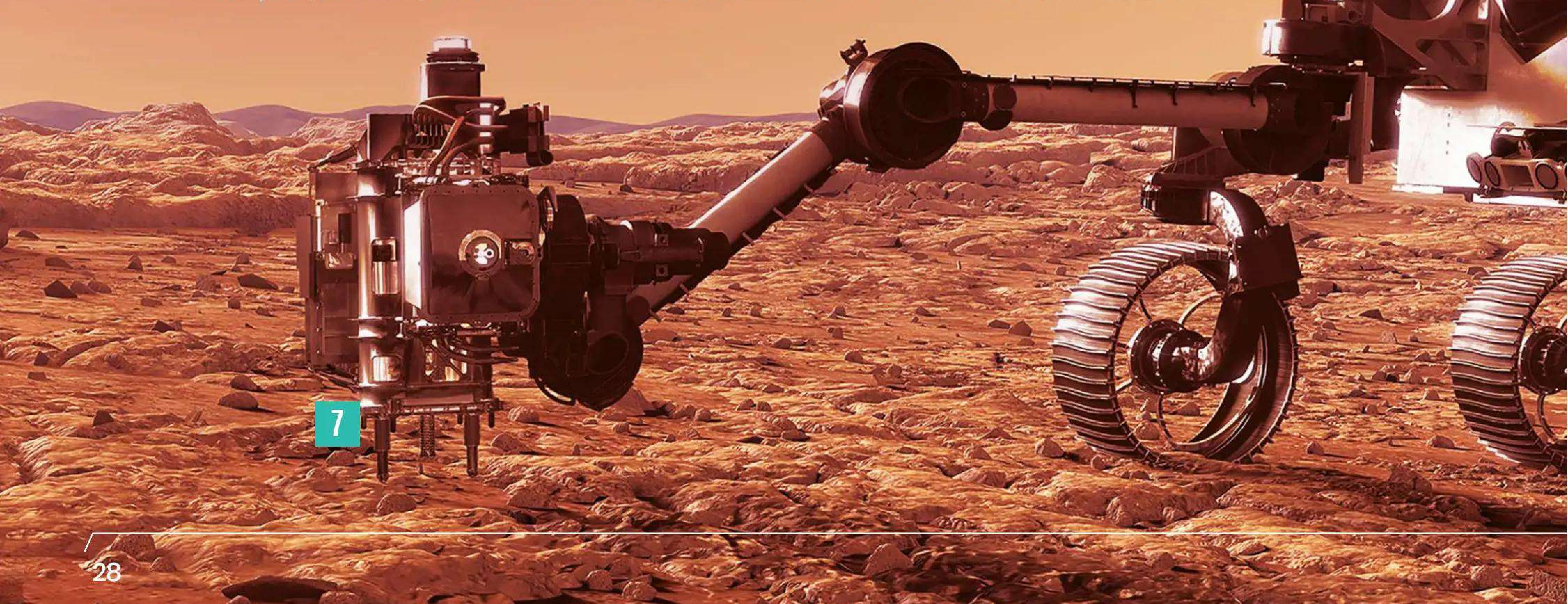
Reported by Keith Cooper

The Curiosity rover has detected intriguing chemical evidence in the form of anomalous amounts of manganese oxide, pointing to Mars having had not only a habitable environment billions of years ago, but also one possibly inhabited by microbes. NASA's Curiosity is exploring the giant 154-kilometre (96-mile) diameter Gale crater, where the rover landed in 2012. Curiosity's discoveries have already established that the crater was at least partially flooded long ago – although the evidence for this has been contested. However, the rover's latest findings not only strengthen the argument for an ancient lake, but also suggest that conditions within the lake were conducive to life.

The evidence is associated with the compound manganese oxide. Curiosity first found small quantities of manganese oxide in Gale crater in 2016, but now it has discovered much greater abundances of manganese oxide in the sedimentary bedrock of a mudstone geological unit called the Murray Formation. The Murray Formation is found on the flank of Mount Sharp in the middle of the crater. The manganese oxide was identified by Curiosity's Chemistry and Camera complex (ChemCam), which fires a laser at rocks that scientists wish to study. The laser heats a small patch of a rock's surface, thereby vaporising it, which results in a small cloud of plasma that ChemCam's onboard camera and spectrometer can study from a distance to determine the ablated material's composition.

ChemCam discovered mudstone that was enriched in manganese oxide by up to 45 per cent. On Earth, manganese oxide is commonly found in lakebeds or river deltas where there are high oxidising conditions. Furthermore, microbes that exist in those environments are able to help catalyse the oxidation process. Usually, this process requires a steady stream of oxygen, which is in short supply on Mars.

The previously discovered small amounts of manganese oxide found on Mars in 2016 can be explained without significant quantities of oxygen, but the large abundances discovered in the Murray Formation are another matter entirely. To reach such abundances, the oxidation



process would require a significant amount of oxygen. “It’s difficult for manganese oxide to form on the surface of Mars, so we didn’t expect to find it in such high concentrations in a shoreline deposit,” said Patrick Gasda of Los Alamos National Laboratory. “On Mars, we don’t have evidence for life, and the mechanism to produce oxygen in Mars’ ancient atmosphere is unclear, so how the manganese oxide was formed and concentrated here is really puzzling.”

One clue is in the nature of the mudstone sediments the manganese oxide was found in. The rocks enriched in manganese oxide were found at a location between two geological units in the Murray Formation. One unit is nicknamed Sutton Island and seems to represent sediments laid down at the edge of a lake; the other, nicknamed Blunts Point, would have been deeper in the lake. The manganese-oxide-enriched mudstone is coarser, with larger grains than bedrock elsewhere in the crater where only small abundances of the compound have been discovered. The larger grains would have contributed to forming a more porous bedrock than the fine-grained mudstone seen elsewhere in Gale crater – mudstone that is presumably from much deeper in the lake.

This porosity would have allowed groundwater to pass through more freely. The manganese could have percolated out of this groundwater as it passed through the coarse-grained mudstone, thus becoming concentrated within the rocks. However, where the oxygen came from to oxidise it remains a puzzle.

THE ROVER’S SUITE

Curiosity has a range of instruments on board to investigate Mars

1 Communication antennae

The antennae allow the rover to communicate with the mission team on Earth. An ultra-high frequency antenna allows for fast data transfers. Low-gain and high-gain antennae transmit more data at higher frequencies, but are more narrowly focused.

2 Environmental sensors

The Curiosity rover measures atmospheric pressure, humidity, temperature, wind speed and direction and ultraviolet radiation on the surface of Mars, providing daily and seasonal reports on these factors.

3 Laser analysis

Curiosity is fitted with ChemCam, an instrument that fires a laser at the ground and determines which rock and soil targets are of potential interest by analysing their elemental compositions. It can also take detailed images.

4 Photos and video

These two Mast Cameras can take colour images and video so that scientists can better navigate the rover, direct rock sampling and gain panoramic views of the landscape.

5 Organic material

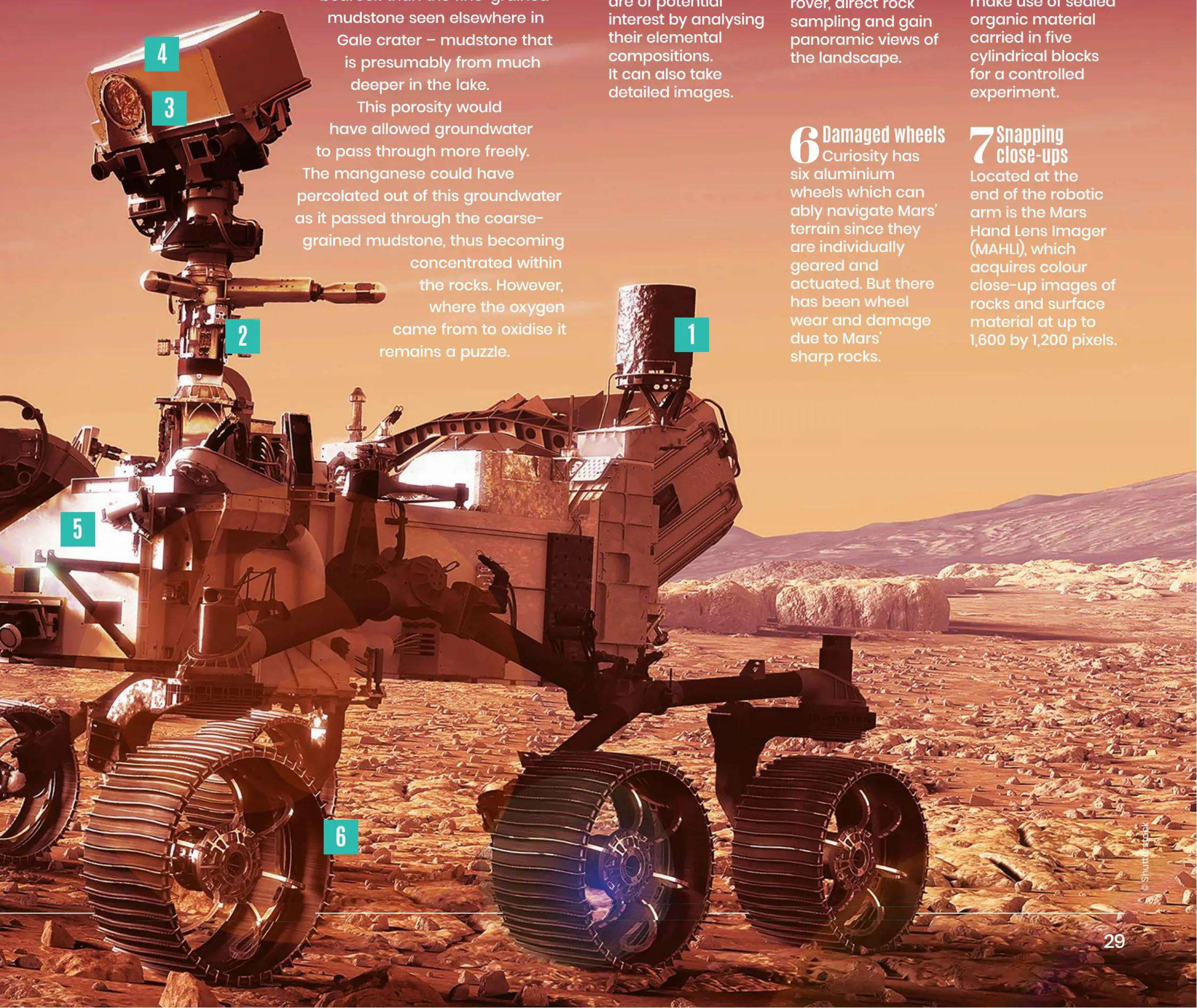
If Curiosity’s Sample Analysis at Mars (SAM) instrument detects organic compounds in the soil or rock, it will make use of sealed organic material carried in five cylindrical blocks for a controlled experiment.

6 Damaged wheels

Curiosity has six aluminium wheels which can ably navigate Mars’ terrain since they are individually geared and actuated. But there has been wheel wear and damage due to Mars’ sharp rocks.

7 Snapping close-ups

Located at the end of the robotic arm is the Mars Hand Lens Imager (MAHLI), which acquires colour close-up images of rocks and surface material at up to 1,600 by 1,200 pixels.



KING of the SOLAR SYSTEM

JUPITER IS THE BIGGEST PLANET IN OUR SOLAR SYSTEM BY FAR. HERE'S SOME ESSENTIAL FACTS ABOUT OUR COLOSSAL NEIGHBOUR

Written by Giles Sparrow

© Alamy

Introducing Jupiter

As the fifth planet from the Sun, Jupiter is the innermost and largest of four giant worlds that dominate the outer Solar System. With a diameter of 144,000 kilometres (89,477 miles) across the equator, it's more than 11 times wider than Earth – although a rapid rotation period of just 9 hours and 55 minutes produces a pronounced equatorial bulge where fast-moving material attempts to escape Jupiter's gravity. While the small rocky planets are all crammed fairly close together, the giants are much more widely spaced – Jupiter's orbit ranges between 741 and 816 million kilometres (460 and 507 million miles) from the Sun, with Saturn, Uranus and Neptune even more broadly spaced out beyond it. Despite its distance, Jupiter's sheer size and the brightness of its cloud tops mean that it reflects a great deal of sunlight, allowing it to outshine everything but Venus and the Moon in our skies. Its disc and dark cloud belts are visible even through small telescopes, and the dance of its four largest moons can be traced with binoculars.

> "Jupiter's sheer size and the brightness of its cloud tops mean that it reflects a great deal of sunlight"

1 Surface
The visible surface of Jupiter is mostly ammonia crystals and sulphur, forming swirling clouds.

2 Orbit
Jupiter orbits the Sun at an average of 778 million kilometres (485 million miles).

3 Body
Jupiter is built up of layers. The closer to the core it gets, the denser the layers are.

4 Great Red Spot
This storm on Jupiter's surface has been raging for at least 350 years and is three times larger than Earth.

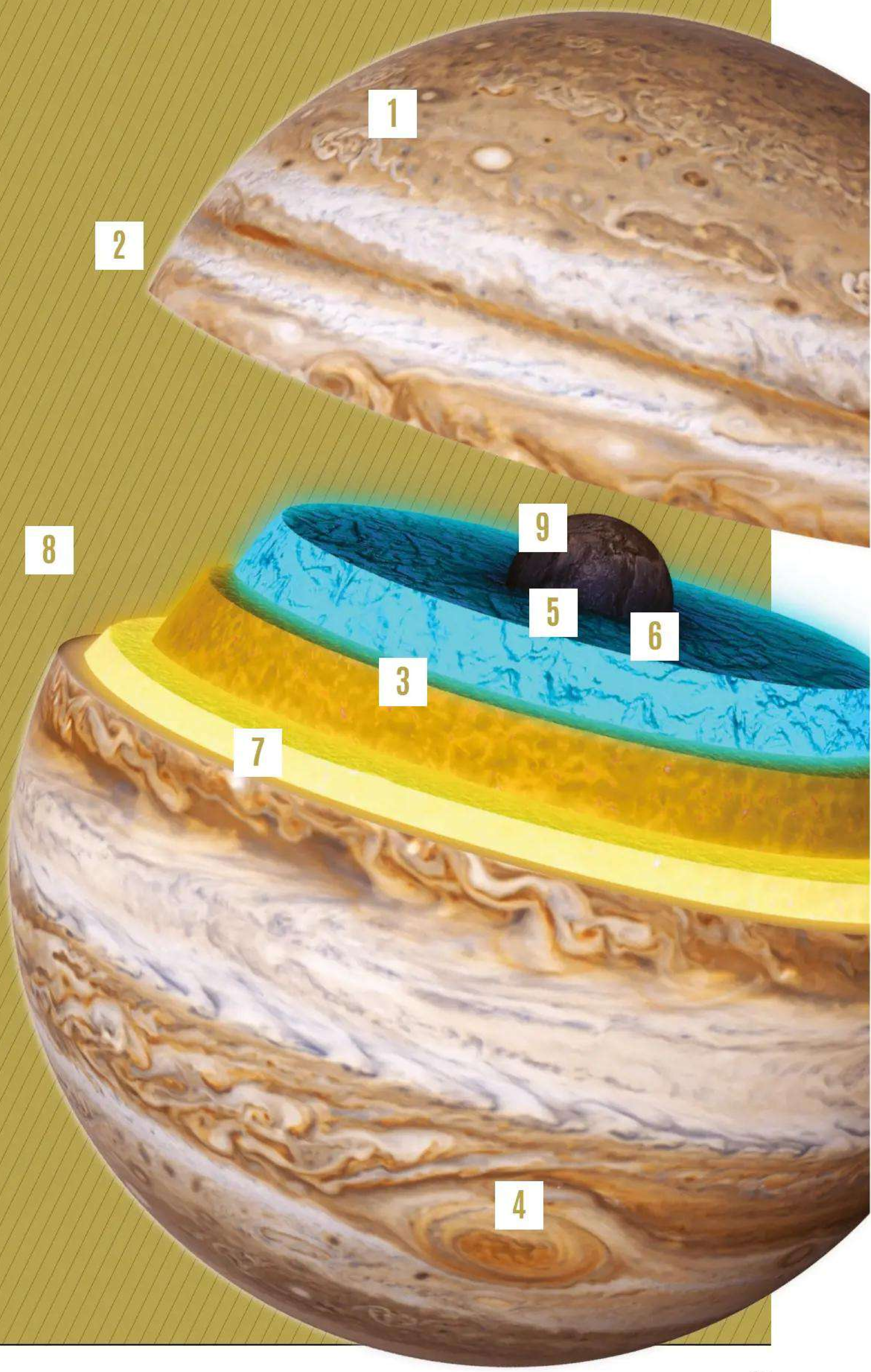
5 Gravity
The mass of Jupiter's core means that gravity on the planet is 2.4 times that felt on Earth.

6 Temperature
The core of Jupiter is an incredibly hot 35,000 degrees Celsius (63,000 degrees Fahrenheit).

7 Composition
90 per cent of Jupiter is hydrogen. Ten per cent is helium, and there's a tiny smattering of other gases.

8 Ring
It was discovered in 1979 that Jupiter has a ring around it, like Saturn, but Jupiter's ring is much fainter.

9 Core
Jupiter's core is composed of rock surrounded by a layer of metallic hydrogen.



Jupiter by numbers

1310

The number of Earths that could fit inside Jupiter

9,276 kilometres

The difference between Jupiter's equatorial and polar diameter due to its equatorial bulge

11.86 years

Jupiter's orbital period

2.53g

The strength of Jupiter's gravity at its cloud tops compared to Earth's

-110°C

Average temperature at Jupiter's cloud tops

3.1 degrees

Jupiter's tilt relative to its orbit; the small tilt means the planet has negligible seasons

Birth of a giant

Jupiter owes its present size and mass to the location where it formed roughly 4.6 billion years ago. It was the first planet to form in the protoplanetary nebula surrounding the newborn Sun – perhaps just a million years after the Sun itself and tens of millions of years before the rocky inner planets. Evidence suggests that the giant outer planets formed through a process known as pebble accretion, in which huge piles of small pebbles orbiting through the gas of the nebula became unstable and abruptly collapsed under their own gravity to form large protoplanets.

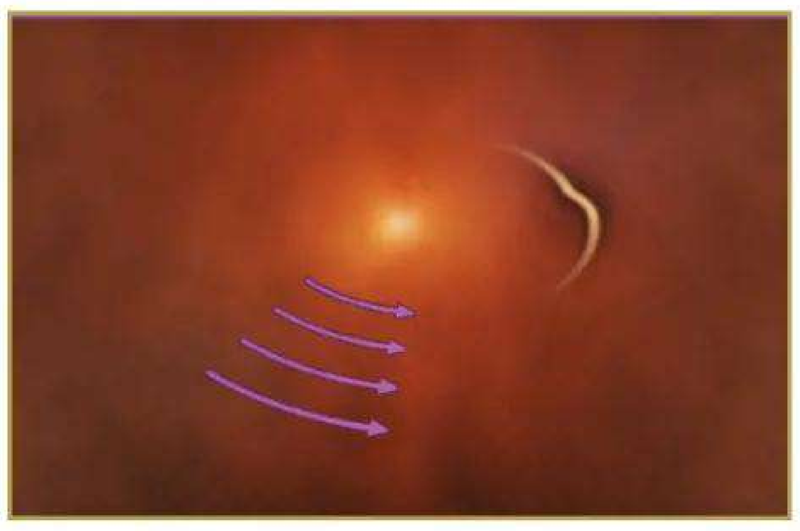
Jupiter formed beyond the frost line of the early Solar System – a region where volatile, easily melted icy chemicals were able to remain frozen. As a result, this region was the richest part of the nebula. Closer in, the Sun's heat caused ices to evaporate, and its solar wind drove them outwards; further out, material naturally became more thinly spread. Nevertheless, as the proto-Jupiter's gravity rapidly pulled in surrounding gas and ice over the next few million years, the growing planet was in a race against the solar wind blowing gases out of its grasp. Quite what form the early core took remains uncertain – not least because of recent discoveries about Jupiter's deep interior.

> "Jupiter was the first planet to form in the protoplanetary nebula"

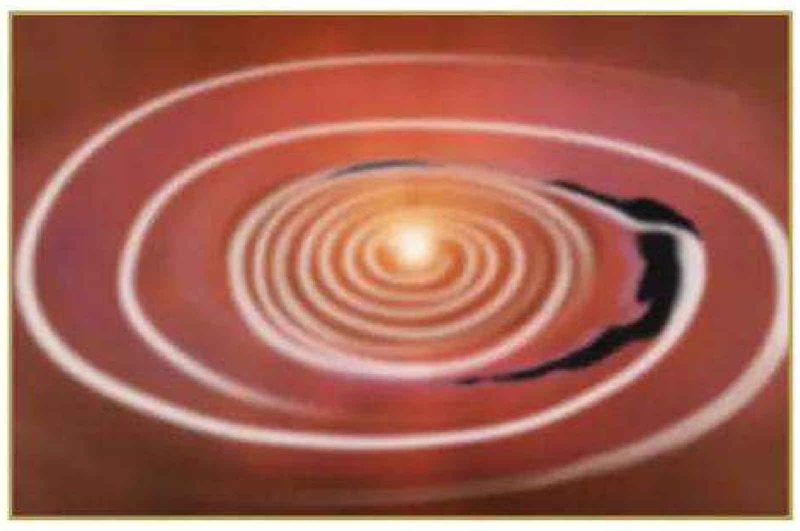
Controlling influence

Despite being composed mainly of lightweight gases, Jupiter has a mass of 318 Earths – almost 2.5 times that of all the other planets combined. Its gravitational influence is felt across a vast expanse of space. Any objects that stray too close are either captured into orbit as satellites, drawn to their doom into its deep, tumultuous atmosphere or have their own orbits around the Sun dramatically altered. For example, Jupiter's gravity gives the asteroid belt between Mars and the gas giant a sharp outer edge, and the planet shepherds other asteroids that attempt to share or cross its orbit into two clouds known as trojans. Orbiting 60 degrees behind and in front of Jupiter itself, these asteroids sit at gravitational balance points where the influence of the Sun's gravity protects them from Jupiter's disruption.

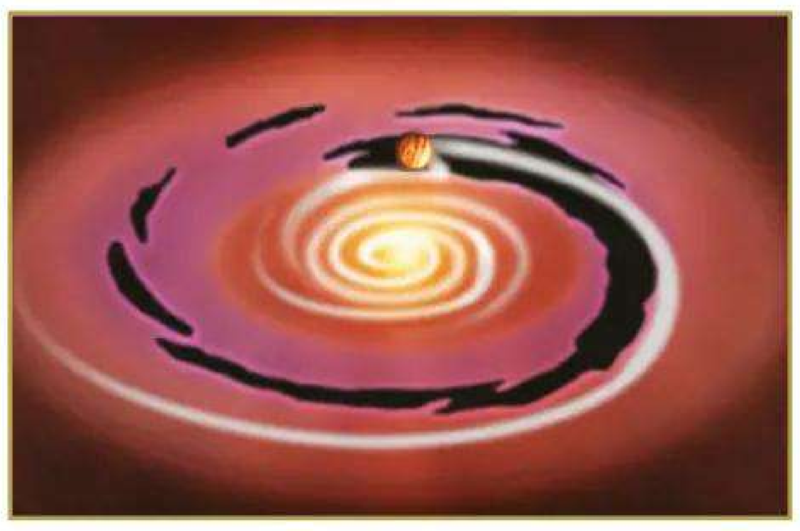
Jupiter also has a profound influence on passing comets. As these icy chunks of debris fall towards the Sun on extremely elongated orbits, a close encounter with Jupiter can alter their paths through space. In some cases, they become short-period comets that return to the inner Solar System every few years or decades. In other cases, Jupiter's gravity may rip a comet to shreds before the giant planet absorbs it completely. For this reason, Jupiter is sometimes regarded as a guardian of the Solar System, protecting the inner planets – including Earth – from violent space impacts.



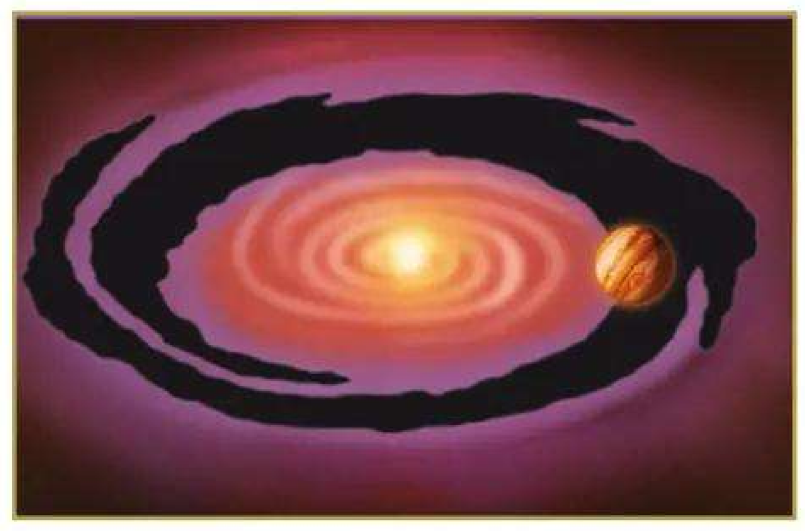
1 The start of a system
Dust grains in orbit around our young star began to coalesce into planetesimals.



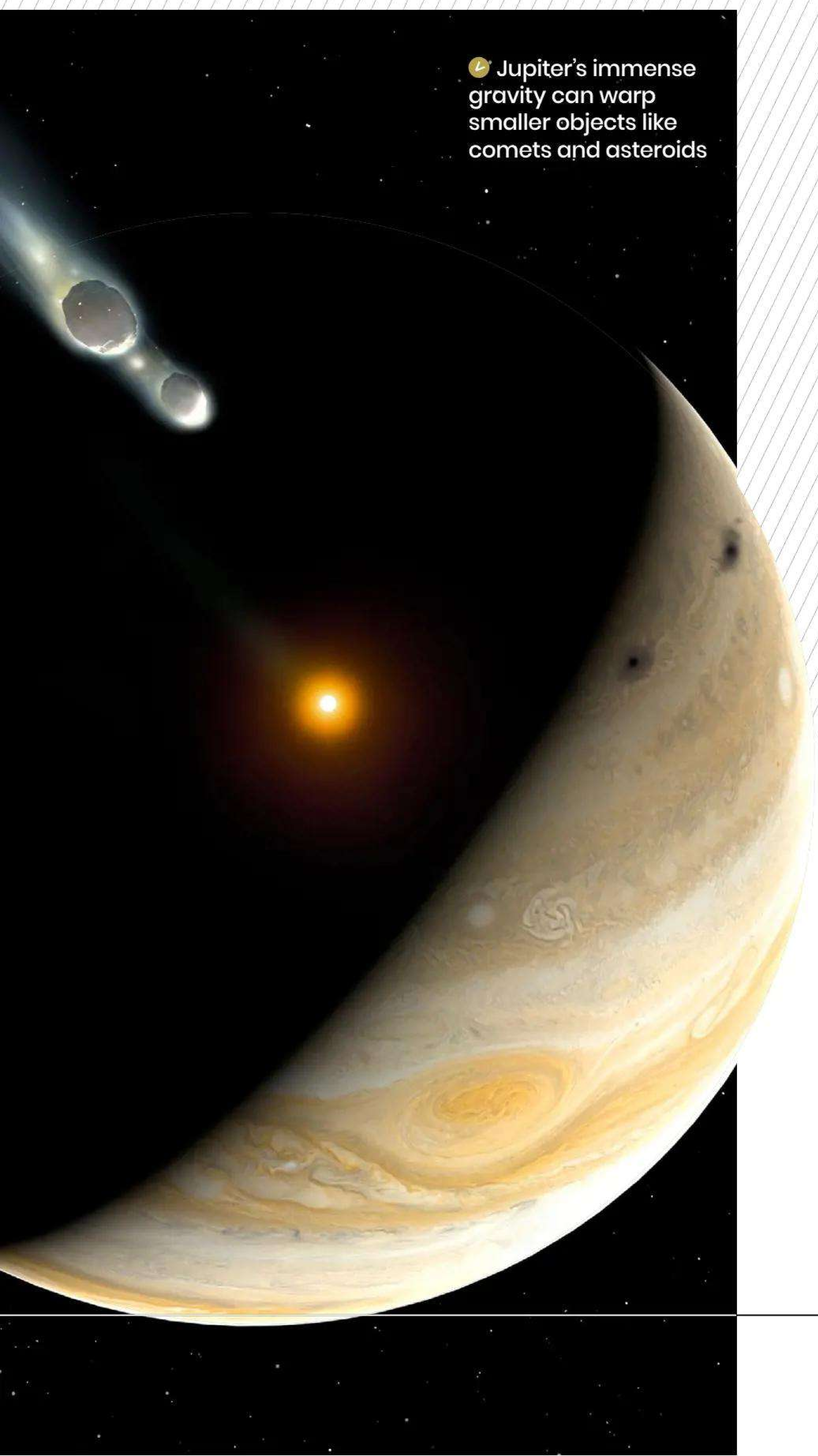
2 Growing into planets
The sizes of these planetesimals began to increase, moving in orbits to form planetary embryos.



3 The making of a gas giant
Before the gas in the disc disappeared with the solar wind, the planetesimals dragged gas envelopes onto themselves, giving them puffy layers.



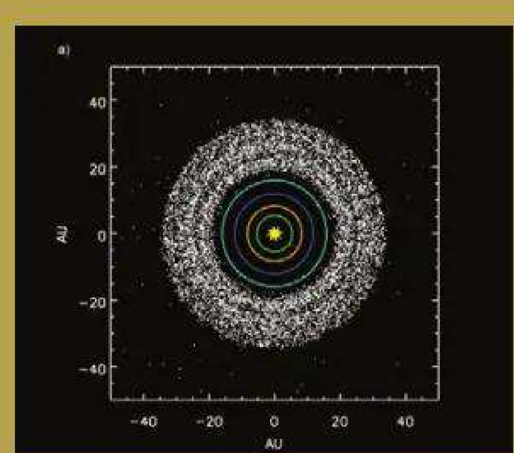
4 Planetary scatter
Some of the gas giant planets scattered. Due to their sheer size, they accreted the remaining planetesimals and embryos.



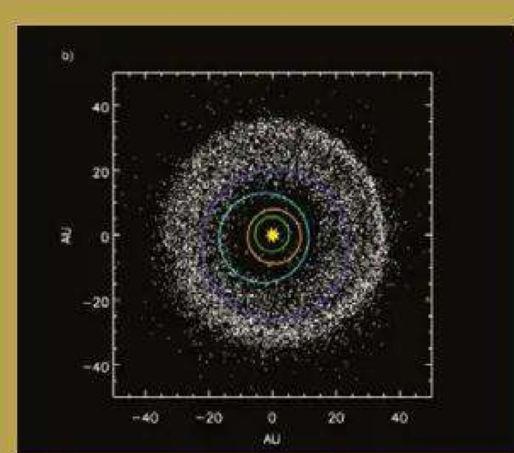
Jupiter's immense gravity can warp smaller objects like comets and asteroids

Wandering world?

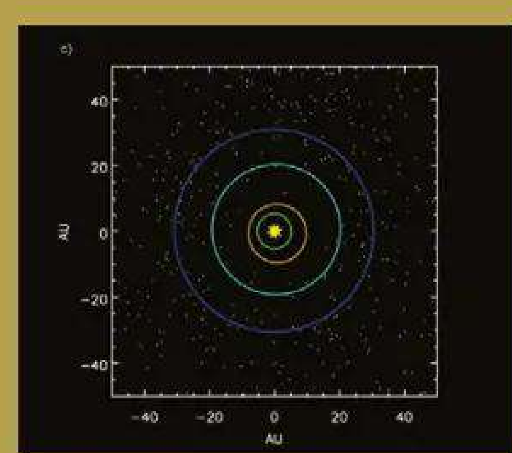
In order to explain the early history of the Solar System as a whole, astronomers have proposed several theories in which Jupiter formed at a different distance from the Sun and migrated to its current position, perhaps over a million years or less. The most widely accepted of these is called the Nice model. According to this hypothesis, Jupiter and the other giant planets formed much further out in the Solar System than their current positions, initially arranged in quite close-packed orbits around the current location of Neptune. As Jupiter ploughed through clouds of ice-rich debris that then occupied much of the outer Solar System, an exchange of momentum catapulted these smaller worlds to the very edge of the Solar System – where they now form the distant Oort Cloud of dormant comets – while sending Jupiter and the other planets spiralling in towards the Sun. The process only came to a halt when the region around the planets was largely 'cleared out'.



1 Young orbits
After the dissipation of the Solar System's primordial disc, Jupiter, Saturn, Uranus and Neptune could be found on a nearly circular orbit somewhere between 5.5 and 17 astronomical units.



2 Complete chaos
After a slow migration, Jupiter and Saturn caused a regular and periodic gravitational influence on each other, causing eccentric orbits that destabilised the entire Solar System.

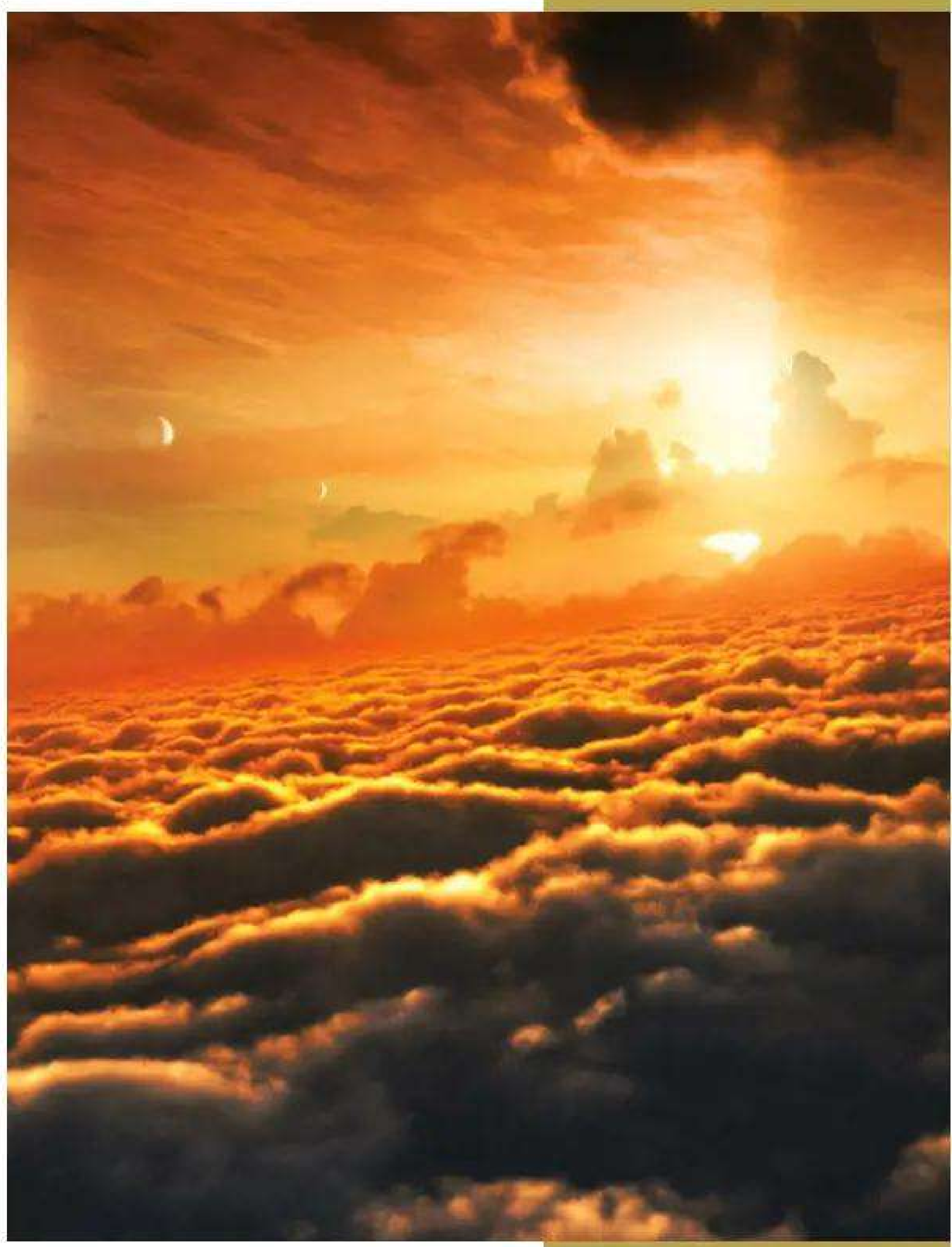


3 A shower of planetesimals
Neptune and Uranus scattered rocks from their orbits to the outer reaches, removing nearly all the primordial disc's mass that once battered the inner planets.

Weather systems

Jupiter's belts and zones are divided along boundaries where strong jets of wind blow alternatingly eastwards and westwards around the planet. Opposing jets on either side of each weather band create sheer forces that twist the features within them in either clockwise or anticlockwise directions. Such features include compact dark spots, elongated 'barges' and wave-like structures called 'festoons'. These all have complex origins that are not fully understood, but many are linked to upwellings of material and interactions between neighbouring regions of high and low air pressure. Storms form at various levels within the atmosphere, often with lightning triggered when the separation of warmer and cooler materials builds up enormous static electric charges.

As on most of the other giant planets, Jupiter's weather is driven mostly by heat escaping from its interior. The planet emits around twice as much energy as it receives from the Sun. This is due to a combination of residual heat from its formation, ongoing internal contraction and chemical reactions in the deep interior. Convection cells transporting warm fluid to the surface and replacing it with cooler material sinking back down are thought to drive a deep-rooted circulation pattern with consequences we see at the surface. According to this model, the zones represent upwellings of material that pile up to greater heights and form cool, bright clouds on its upper surface. The belts, meanwhile, mark downwelling material where the upper clouds evaporate to expose the deeper, warmer layers.



1 Oval storms These small white storms roll across the planet, occasionally merging and forming larger, redder storms.

2 Equatorial Zone This zone is one of the more stable regions on Jupiter, without as much activity and with constant wind shear. It's sometimes bisected by a dark belt.

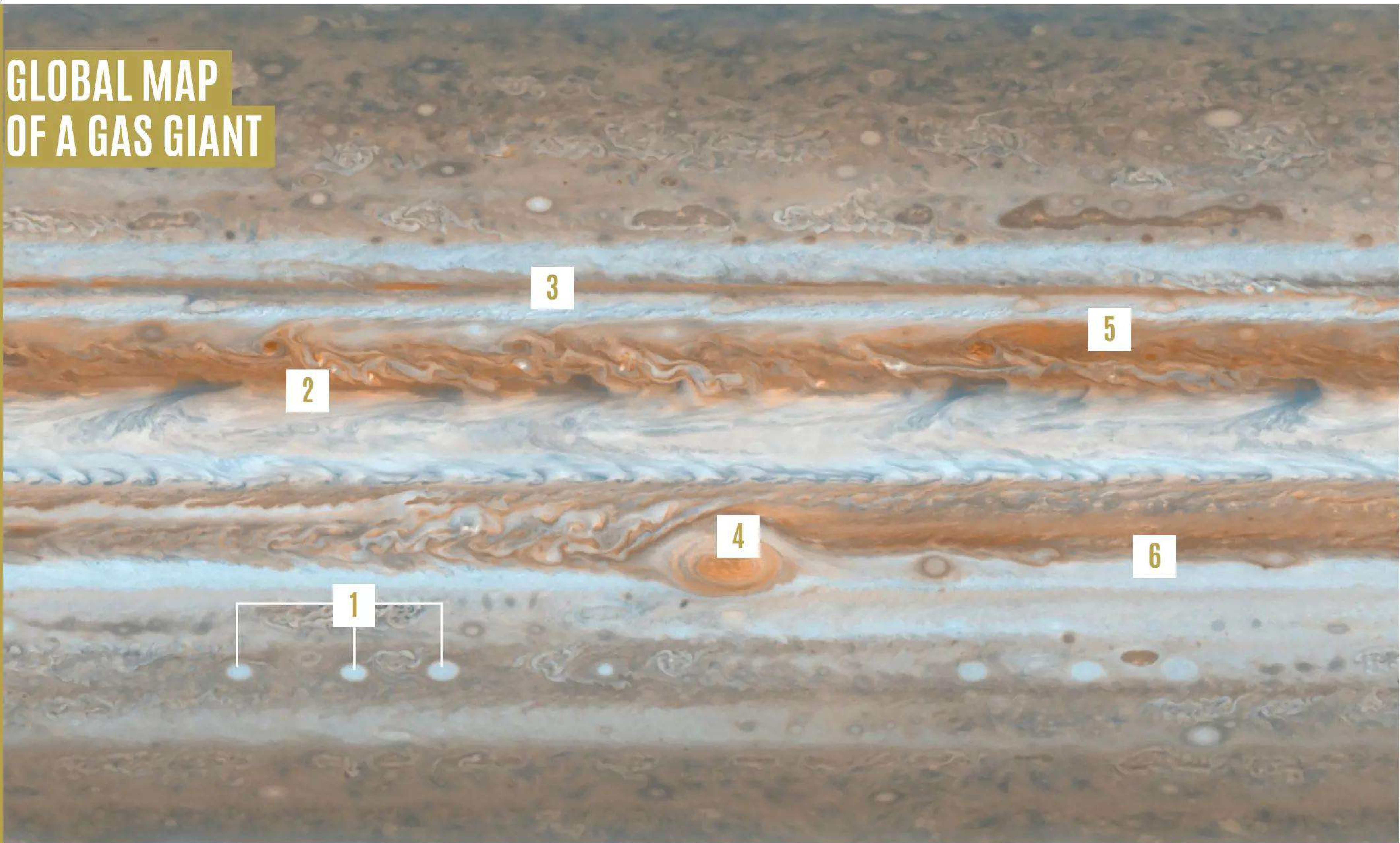
3 North Temperate Belt This belt comprises the strongest prograde, or eastward, belt on the planet. It fades once every ten years, causing the surrounding zones to merge.

4 Great Red Spot Jupiter's most visible feature, the GRS has been around for hundreds of years and is a strong anticyclonic storm that could fit two to three Earths inside it.

5 North Equatorial Belt One of the most active areas on the planet, it contains short-lived storms in the form of small, white anticyclonic ovals and brownish cyclonic storms.

6 South Equatorial Belt This belt is usually the planet's widest and darkest. It sometimes vanishes and reforms from a single white spot that exudes dark material, which is stretched by wind.

GLOBAL MAP OF A GAS GIANT



Cloud layers

Jupiter's most prominent features are dark and light cloud bands that wrap their way around the planet. Known as belts and zones respectively, they are named for their positions on the planet. The large pale band in the middle of the planet, called the Equatorial Zone, is flanked by dark north and south equatorial belts, with the light north and south tropical zones beyond them, and so on. The distinctive banding extends roughly halfway from the equator to the poles, at which point it gives way to the more turbulent polar regions. They are stable in the long term, but certain regions are prone to split, merge or change colour and visibility every few years before eventually returning to 'normal'.

Although the names belt and zone imply that we're seeing dark features that are overlaid onto a paler, deeper background cloud layer, the opposite is actually the case – space probe measurements have shown that the bright clouds of the zones are a few kilometres higher, in a cooler region of the atmosphere, while the dark belts are marked by deeper, warmer clouds. Their contrasting appearance is clearly due to various atmospheric chemicals condensing to form clouds in different conditions. Ammonia ice explains the light colour of the zones, while the lower belt clouds are at least partly made from water vapour, with unknown chemicals responsible for their brown and blue colouration. In total, Jupiter's cloud layer is thought to be up to 50 kilometres (31 miles) deep.

7 North polar region

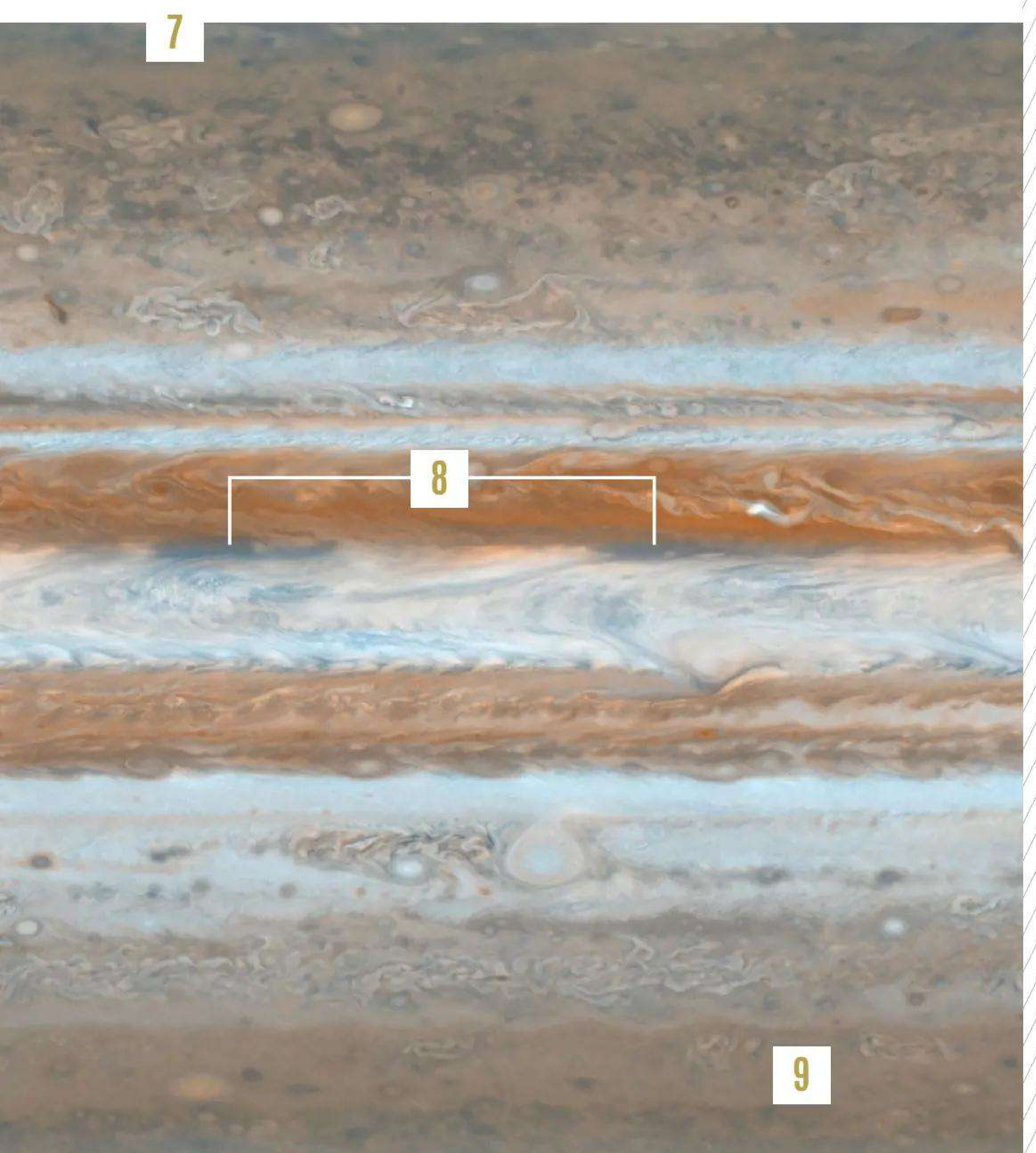
In contrast to the rest of the planet, the poles are dark, blurred areas without much change.

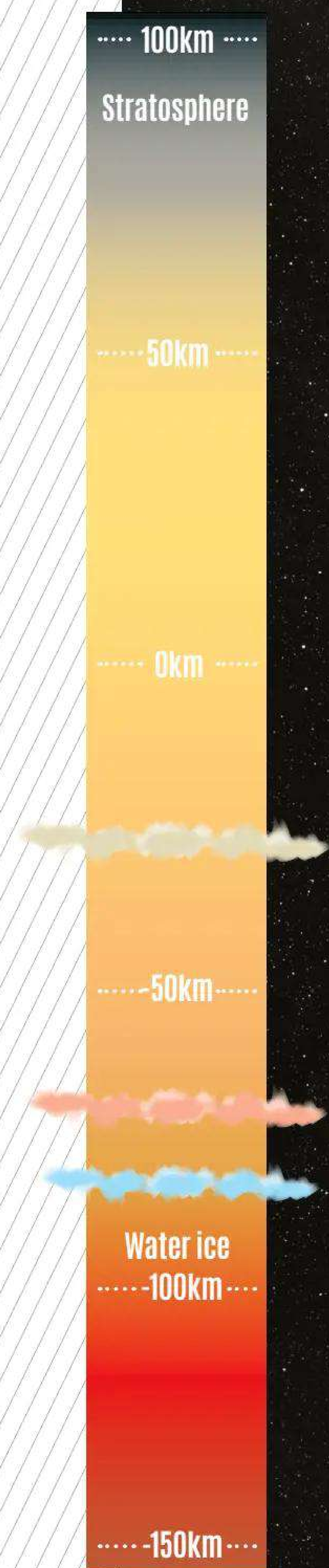
8 Hotspots

Also known as festoons, these greyish-blue spots are a bit of a mystery. There are few clouds here, allowing heat to escape from the gas layer below.

9 South polar region

Like the north polar region, this area on Jupiter appears to be mostly featureless.





Beneath the surface

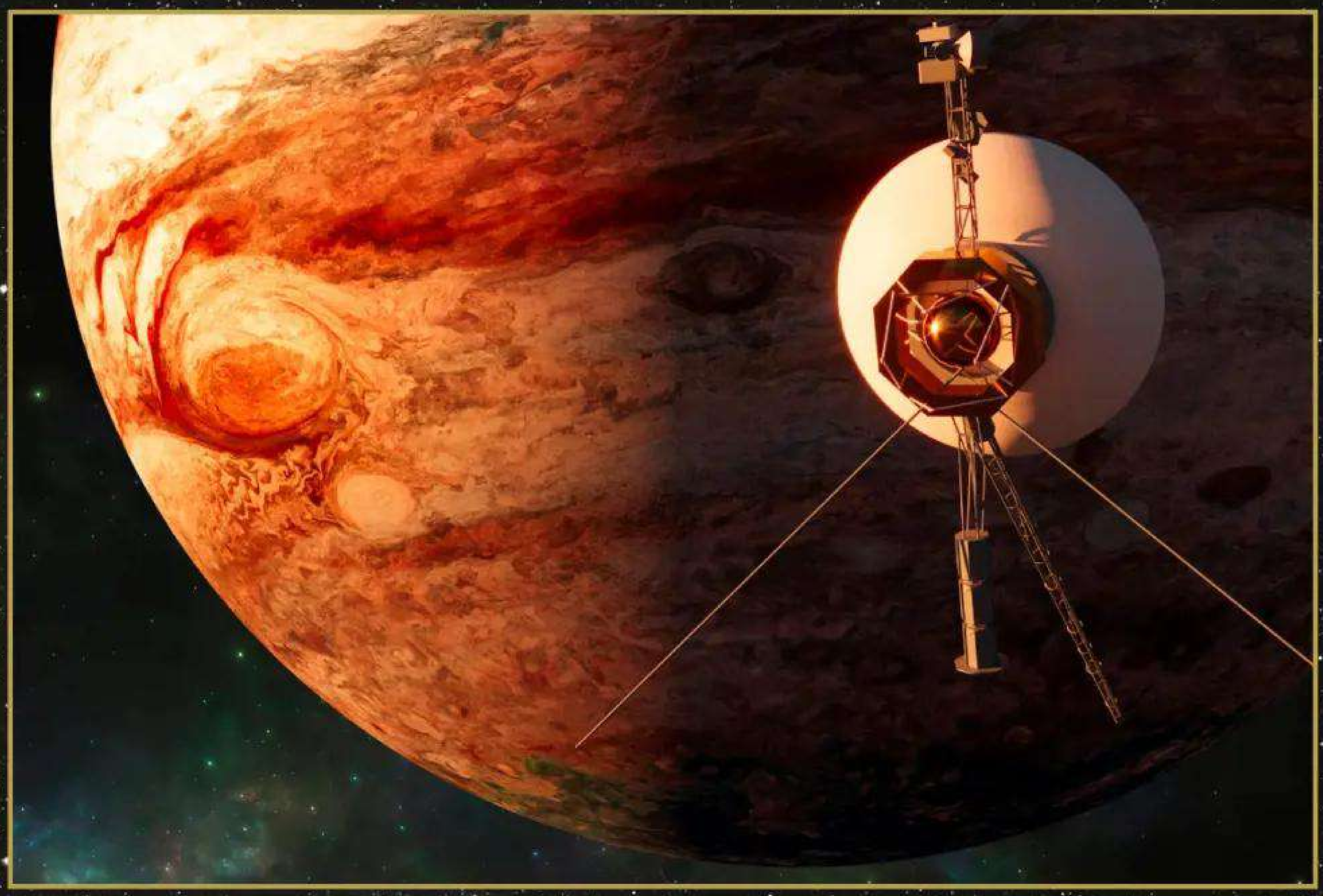
The changing behaviour of hydrogen at increasing depths, pressures and temperatures defines Jupiter's internal layers. About 3,000 kilometres (1,864 miles) below the planet's visible surface, the pressure becomes so great that molecular hydrogen (H_2) should condense into liquid form, but the transition zone is blurry, and because temperatures are high, the hydrogen actually forms a 'supercritical fluid' that can exhibit both gas-like and liquid properties. Around 10,000 kilometres (6,213 miles) down, hydrogen molecules break down into electrically charged ions and form a sea of liquid metallic hydrogen. As this liquid swirls around the planet, it plays a key role in generating Jupiter's powerful magnetic field.

At the top of this liquid metallic ocean, helium condenses into droplets that rain down through their surroundings. Other heavy elements also sift down towards the planet's centre, but recent measurements from the Juno space probe reveal that Jupiter does not have the solid centre we might expect – instead the planet's 'core' is a diffuse region of denser material with about half of Jupiter's overall diameter. The nature of today's core may be an indication that the initial protoplanetary core never became solid in the first place. Alternatively, it may have been disrupted by a head-on collision between Jupiter and another large protoplanet shortly after its formation.

The Great Red Spot

The Great Red Spot (GRS) is Jupiter's most famous feature. Studied since at least 1831 – though it may be centuries older – it's a vast anticyclone, embedded in the South Equatorial Belt at a latitude of 22 degrees south. Despite first appearances, the GRS is the highest feature visible on the planet – the red cloud tops sit about eight kilometres (five miles) above the surrounding belt clouds. However, these cloud tops are just the top of a vast upwelling that draws material from as far as 240 kilometres (149 miles) beneath Jupiter's surface. Infrared images show that material reaching the surface forms a warm ring around a cooler 'eye' and edges where it overturns and begins to descend.

The chemistry behind the spot's colour is unknown, but as with the colour in Jupiter's belts, it's probably due to the mix of compounds it draws to the surface. The spot's intensity can vary considerably, and at times can even disguise itself completely, remaining visible only as a 'hollow' in the surrounding cloud bands. A comparison with other storms that occasionally merge, expand and deepen in colour suggests that a similar process formed the GRS. Despite its long life, it may not be immortal; since the mid-20th century its east-west diameter has reduced dramatically, and it's predicted to become circular in the next decade or two.



The first clear, close-up image of the GRS was taken by Voyager 1 in 1979

16,350

The length, in kilometres, of Jupiter's Great Red Spot

22°

The GRS is 22 degrees south of Jupiter's equator

6

Number of Earth days taken for the Great Red Spot to rotate counterclockwise

400

Minimum number of years that the storm is believed to have lasted

680

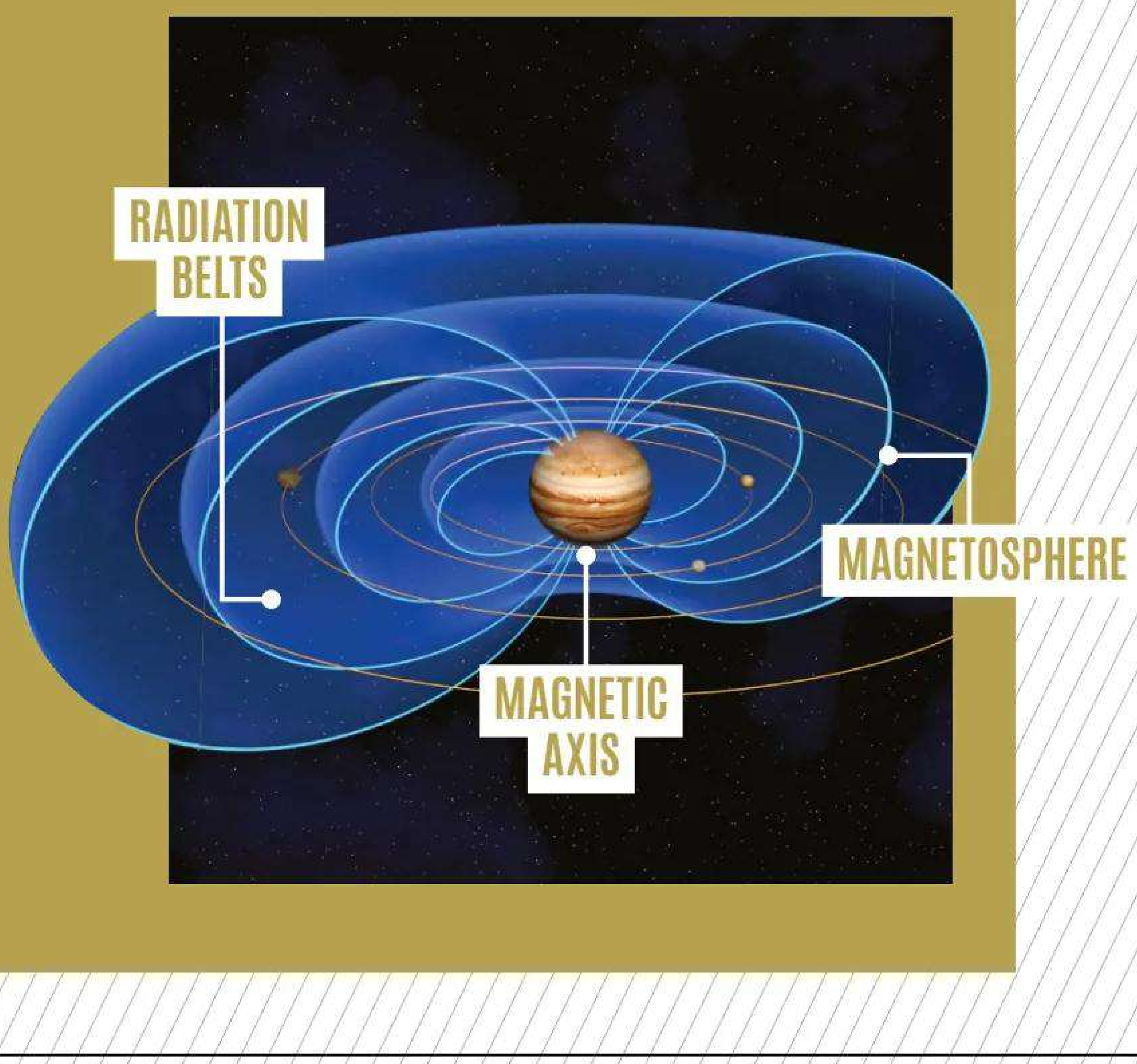
Speed of the winds on the oval edges in kilometres per hour

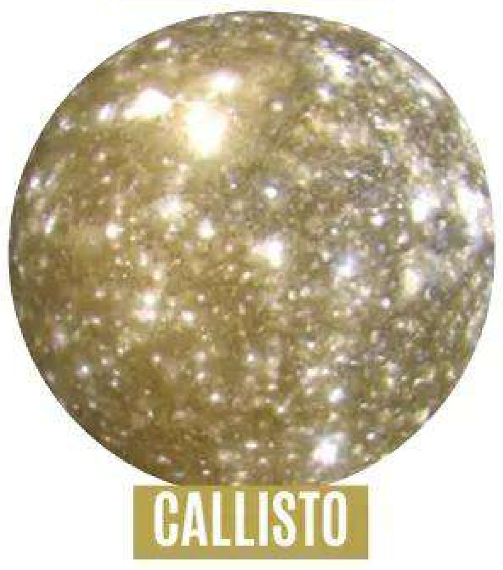
> "The spot's intensity can vary considerably, and at times it can even disguise itself completely"

Magnetism and radiation

Alongside its powerful gravity, Jupiter rules its surroundings through another powerful force – electromagnetism. As the metallic-hydrogen ocean churns deep inside the planet, the electric currents within it act as a huge dynamo, producing a magnetic field. Technically, the field's strength is roughly 20 times that of Earth's, but the planet's vast size and fast rotation mean that it wields 20,000 times the effect on susceptible nearby objects. As a result, Jupiter is surrounded by a truly vast magnetosphere – a region of magnetic influence that reaches out even beyond the orbit of Saturn.

As the magnetic field sweeps up particles from the solar wind – the fast-moving stream of material blowing out from the Sun across the Solar System – it channels them down onto the planet's poles, where they collide with the upper atmosphere and produce spectacular aurorae. Jupiter's large inner moons Io, Europa and Ganymede, meanwhile, create channels within the overall magnetic field, revealed as bright hotspots circling within the auroral ovals above each pole. Meanwhile, some solar wind particles – along with material erupting from the volcanic surface of Io – are trapped in doughnut-shaped belts around the equator, where the magnetic field accelerates them to high speeds and makes them hazardous for visiting spacecraft. Electric currents flowing through the belts turn Jupiter into a strong source of radio emissions.





Orbiting a giant

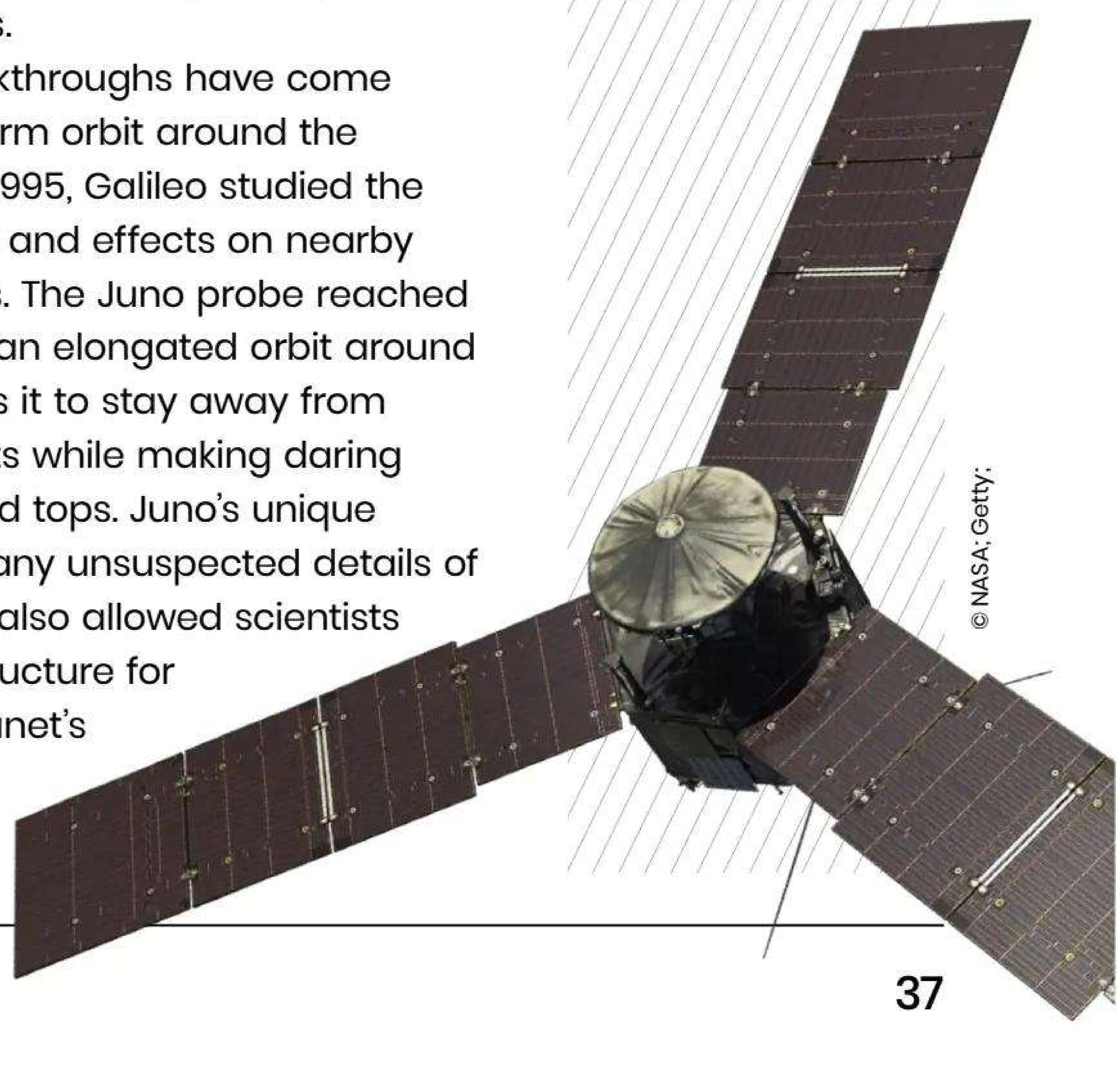
Jupiter's gravity holds at least 95 moons in orbit around it. The largest and best known – called the Galilean moons after Galileo Galilei, the first astronomer to announce their existence – are Io, Europa, Ganymede and Callisto. They vary in size from Europa, which is slightly smaller than Earth's Moon, to Ganymede, the largest moon in the Solar System, bigger than the planet Mercury, with orbital periods ranging from 42.5 hours for Io to 16.7 days for Callisto. The outer three Galilean moons contain a mix of rock and ice, while Io is rocky with a large amount of sulphur. Caught in a gravitational tug of war between Jupiter and their large outer siblings, both Io and Europa experience intense tidal heating that powers volcanic activity. In Io's case this results in abundant surface volcanoes, while on Europa the volcanism is hidden by a thick icy crust and occurs on the seabed of a vast global ocean.

Four much smaller inner moons – Metis, Adrastea, Amalthea and Phoebe – orbit closer in than Io. The bombardment of their surfaces by micrometeorites is thought to provide the dust that maintains a very tenuous ring system around their orbits. While these inner moons are 'regular' satellites, formed from the debris left behind after Jupiter's formation, all the other moons are 'irregular' objects – stray asteroids and comets captured throughout Jupiter's long history following a variety of elongated and tilted orbits.

Exploring Jupiter

Although Jupiter's huge size allows many of its larger features to be studied from Earth, most of our modern knowledge of the planet comes from a handful of space probes that have visited it since the 1970s. Pioneers 10 and 11 made the first flybys of the giant planet in 1973 and 1974, returning the first close-up images of Jupiter and measuring its powerful magnetic field. They were followed by Voyager 1 and 2, which flew past the planet within three months of each other in 1979, sending back detailed images of the Jovian weather systems, as well as discovering its rings and three of its innermost moons.

Many more scientific breakthroughs have come from two missions in long-term orbit around the planet. Arriving at Jupiter in 1995, Galileo studied the gas giant's weather systems and effects on nearby space for almost eight years. The Juno probe reached Jupiter in July 2016, entering an elongated orbit around the planet's poles that allows it to stay away from the dangerous radiation belts while making daring close passes above the cloud tops. Juno's unique perspective has revealed many unsuspected details of the Jovian atmosphere and also allowed scientists to probe Jupiter's internal structure for the first time through the planet's gravitational effect on the probe's flight path.



NASA's Juno probe has been orbiting Jupiter since 2016, returning a wealth of data on the planet and its moons

SECRETS OF SATURN

SATURN IS OUR SOLAR SYSTEM'S RINGED WONDER. HERE'S WHAT EVERY ASTRONOMY ENTHUSIAST SHOULD KNOW ABOUT IT

Written by Giles Sparrow

SATURN: THE BASICS

Saturn is the sixth planet from the Sun, the second most massive world in the Solar System and the most distant that can easily be seen without a telescope. It orbits the Sun at an average distance of 1.43 billion kilometres (890 million miles) and appears to the naked eye as a moderately bright yellowish star. It's only when seen through a telescope that the planet reveals its most impressive secret – a system of bright rings around its equator that present different views to Earth as Saturn circles the Sun once every 29.45 years. Unlike the rocky worlds of the inner Solar System, Saturn is a gas giant – a huge ball of lightweight gases that compress under their own weight to form a mostly liquid interior. With less than one-third the mass of its inner neighbour Jupiter, it keeps a weaker hold on its outer layers, which expand further, resulting in a planet with roughly 80 per cent of Jupiter's diameter, but an average density lower than water. What's more, Saturn's rapid rotation period of just under 10 hours and 34 minutes means that gas around its equator can attempt to escape its weak gravity, creating a substantial equatorial bulge that makes the planet's diameter almost 12,000 kilometres (7,500 miles) greater measured across its equator than from pole to pole.

ATMOSPHERE

At first glance, Saturn's atmosphere looks rather dull compared to the colourful storms of its inner neighbour Jupiter. However, this is more to do with its muted colours than a lack of activity. Orbiting further from the Sun, a combination of chilly temperatures and low pressures allow ammonia gas to condense in the uppermost cloud layer, forming a white haze that may conceal more colourful clouds below. Beneath the ammonia ice lies a deeper zone in which clouds are made of water ice, mixed for part of its depth with clouds of ammonium hydrosulfide ice. Deep beneath the surface, at atmospheric pressures 10 to 20 times greater than Earth's, clouds of liquid water and ammonia droplets can form.

Clouds account for just a small proportion of Saturn's atmospheric chemistry, and in general the atmosphere is dominated by gaseous molecular hydrogen, the lightest element in the universe. Hydrogen accounts for over 96 per cent of the atmosphere, with helium, the next lightest element, accounting for another 3.25 per cent. These gases condense into liquid roughly 9,000 kilometres (5,600 miles) below the surface, making Saturn's gaseous outer layers about three times deeper than Jupiter's.

1 Ammonia haze

Cold conditions in the upper atmosphere allow ammonia to condense and form bright, hazy clouds at pressures between roughly 0.4 and 1.7 times Earth's atmospheric pressure.

2 Deeper clouds

As pressure increases further, other chemicals condense into droplets and form clouds – in particular ammonium hydrosulfide and a water ice and ammonia mix.

3 Liquefied gas

At a depth of about 1,000 kilometres (621 miles), pressures reach 1,000 Earth atmospheres – enough for hydrogen to condense into its liquid molecular form.

4 Metallic ocean

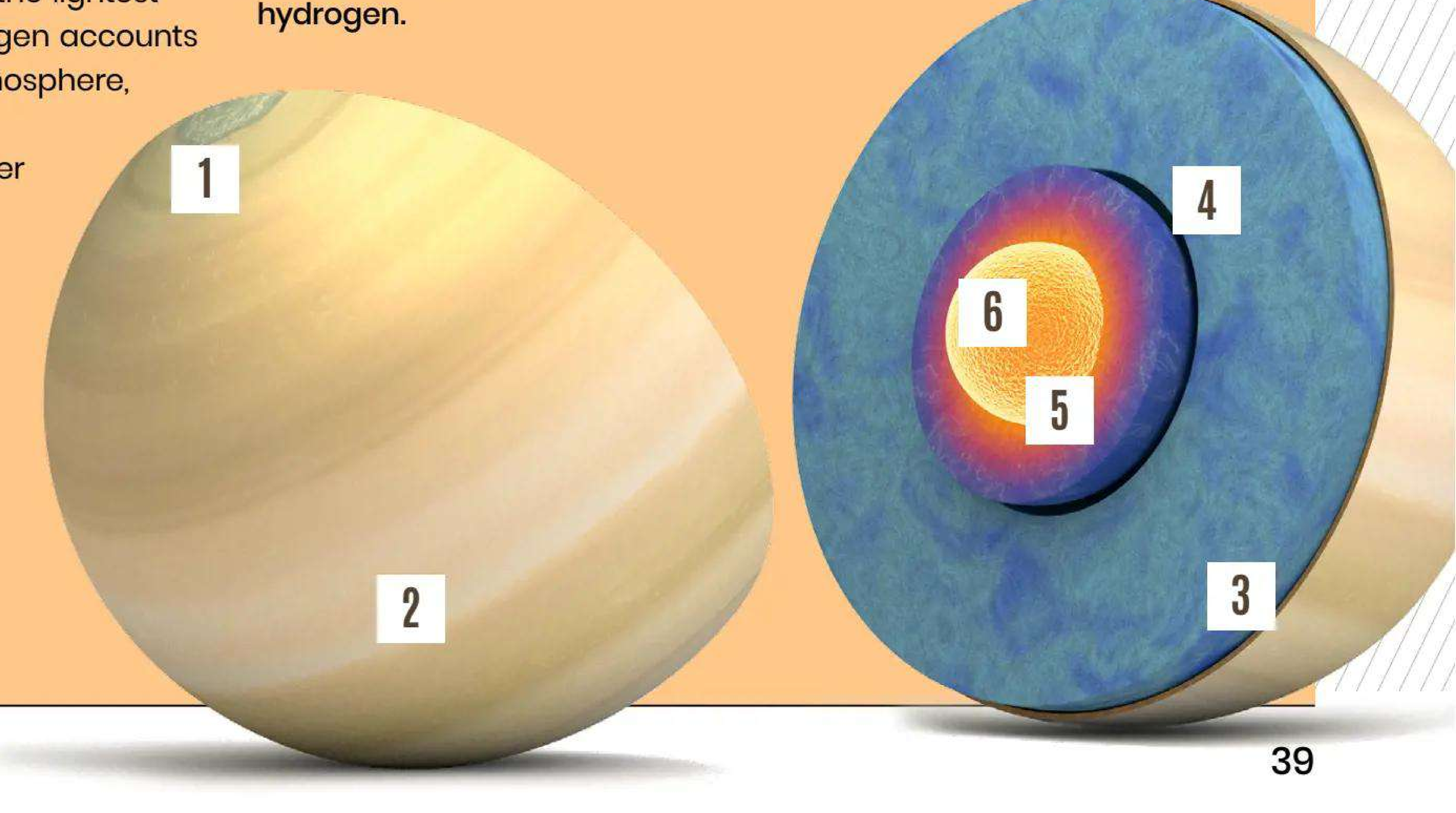
Here pressures reach 2 million Earth atmospheres and temperatures rival the surface of the Sun. Hydrogen molecules split apart to form a sea of electrically charged metallic hydrogen.

5 Fuzzy core

Recent studies suggest Saturn has a fuzzy core that begins where heavy elements mix with the liquid metallic layer. This grows denser towards the centre.

6 Solid centre?

The scientific jury is still out on whether Saturn has a distinct solid core of rock and metal.



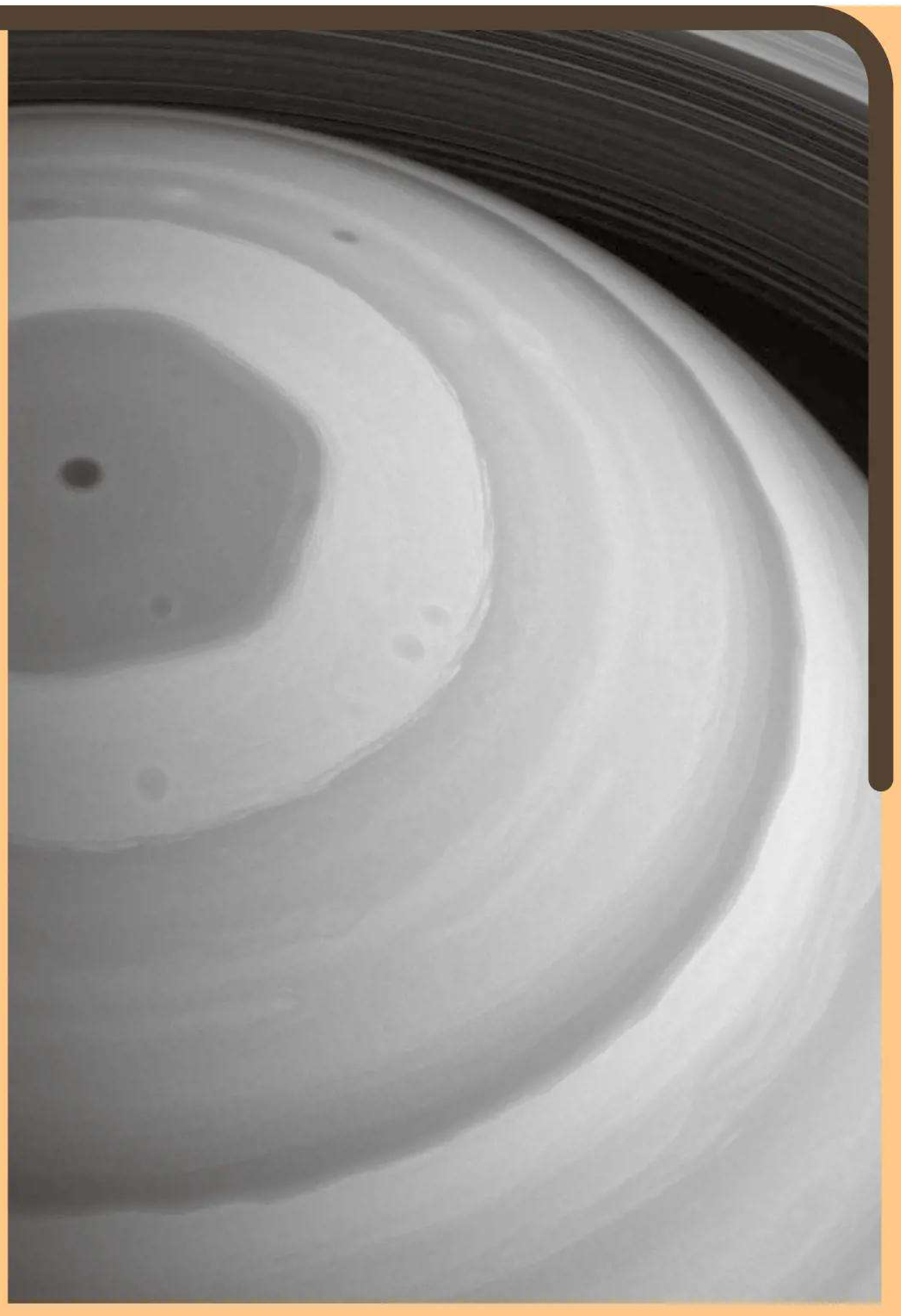
BELTS AND ZONES

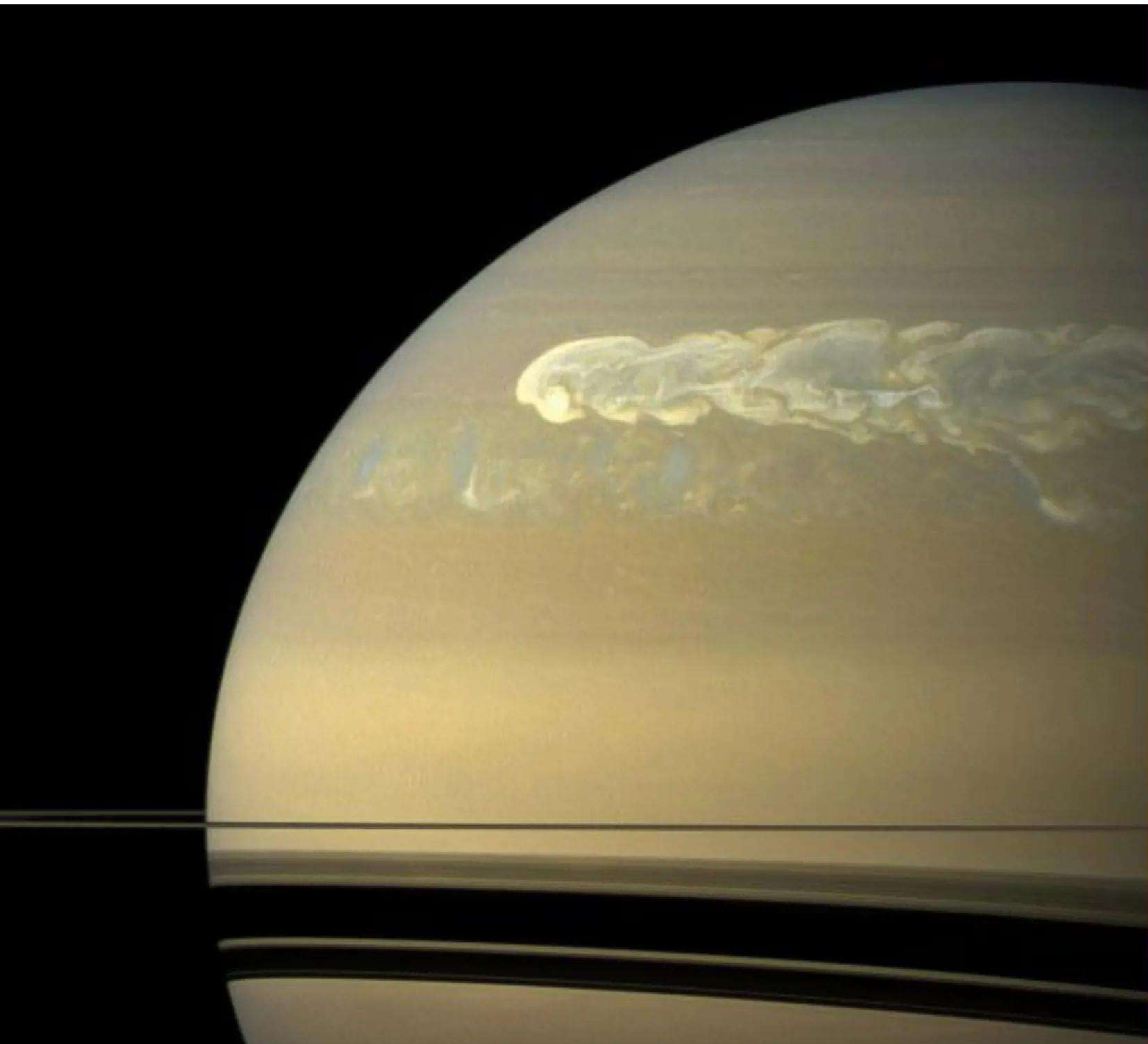
Weather on Saturn is largely driven by energy escaping from inside the planet. Thanks to the processes at work in its deep interior, Saturn pumps out 2.5 times more energy than it receives from the Sun. Heat from inside the planet creates convection cells in which atmospheric gases rise towards the surface, shed their excess heat and then sink again. Saturn's rapid rotation stretches these systems out in bands parallel to the equator, creating alternating regions called belts and zones. Along their boundaries, strong 'zonal winds' blow in opposite directions around the planet. In general, Saturn's belts and zones are broader and less sharply defined than those of Jupiter, but there's still a distinction between darker clouds in the belts and lighter ones in the zones. These names might imply that the belts are higher regions above the zones, but the zones mark regions of upwelling warm material where lighter clouds form at high levels, while the belts are downwelling cooling material whose cloud tops sit lower in the atmosphere.

POLAR MYSTERIES

The polar regions of Saturn are home to long-lived weather systems forever out of sight from Earth. The north polar vortex is a roughly Earth-sized storm whose hexagonal sides precisely match a hexagonal cloud pattern that surrounds the pole at latitude 78 degrees north. This outer hexagon, about 14,500 kilometres (9,000 miles) along each side, is probably a 'standing wave' similar to those produced in stringed musical instruments, but its precise cause – and its link to the polar vortex – are still uncertain. The 8,000-kilometre (4,970-mile) wide south polar vortex, meanwhile, is a circular storm with a vast clearing at its centre, similar to the eye of an Earth hurricane. It marks a spot where rising heat inhibits cloud formation, providing a window into Saturn's deep atmosphere.

Just like Earth and Jupiter, Saturn's poles are also the site of aurorae - brilliant displays of northern and southern lights created as particles trapped by Saturn's magnetic field collide with gases in the upper atmosphere and release energy. Saturn's aurorae are unique in several ways. Electrically charged particles escaping from the icy moon Enceladus leave a distinct 'footprint' in the auroral patterns, while high-speed winds blowing across the north pole at high altitudes are capable of warping the planet's magnetic field and twisting the aurorae out of shape.





STORMY WEATHER

Although Saturn has no obvious permanent weather systems to match Jupiter's centuries-old Great Red Spot, it frequently produces shorter lived storms in the form of white or brown ovals – still hundreds of thousands of kilometres across – which are often seen to occur in chains in certain regions, such as 'Storm Alley', which is around 30 to 40 degrees south of Saturn's equator. The activity in Storm Alley may itself be driven by a vast and long-lived electrical storm called the Dragon Storm, which rages largely unseen deep inside Saturn's atmosphere, but can be detected as countless bolts of lightning generate strong radio signals. For reasons that are poorly understood, the Dragon Storm is only active when it lies on Saturn's night side, becoming dormant in the daytime. Its activity also varies considerably over time, but it can sometimes produce visible flare-ups in the form of prominent white cloud outbreaks.

Saturn's most impressive storm is its 'Great White Spot' – an eruption of brilliant clouds in northern latitudes that occurs roughly every Saturnian year during northern spring or early summer. Great White Spot outbreaks frequently wrap themselves all the way around the planet; their cause is probably something to do with seasonal changes to Saturn's internal temperature and chemistry, and they leave chemical changes in their wake that can still be traced decades later.

> "The activity in Storm Alley may be driven by a vast and long-lived electrical storm called the Dragon Storm"

SATURN BY NUMBERS

120,536 kilometres
Saturn's equatorial diameter

26.7 degrees
The planet's axial tilt, which creates its Earth-like seasons

0.0000027 per cent
The mass of Saturn's rings in comparison to the planet

1,800 kilometres per hour
Fastest wind speeds recorded on Saturn

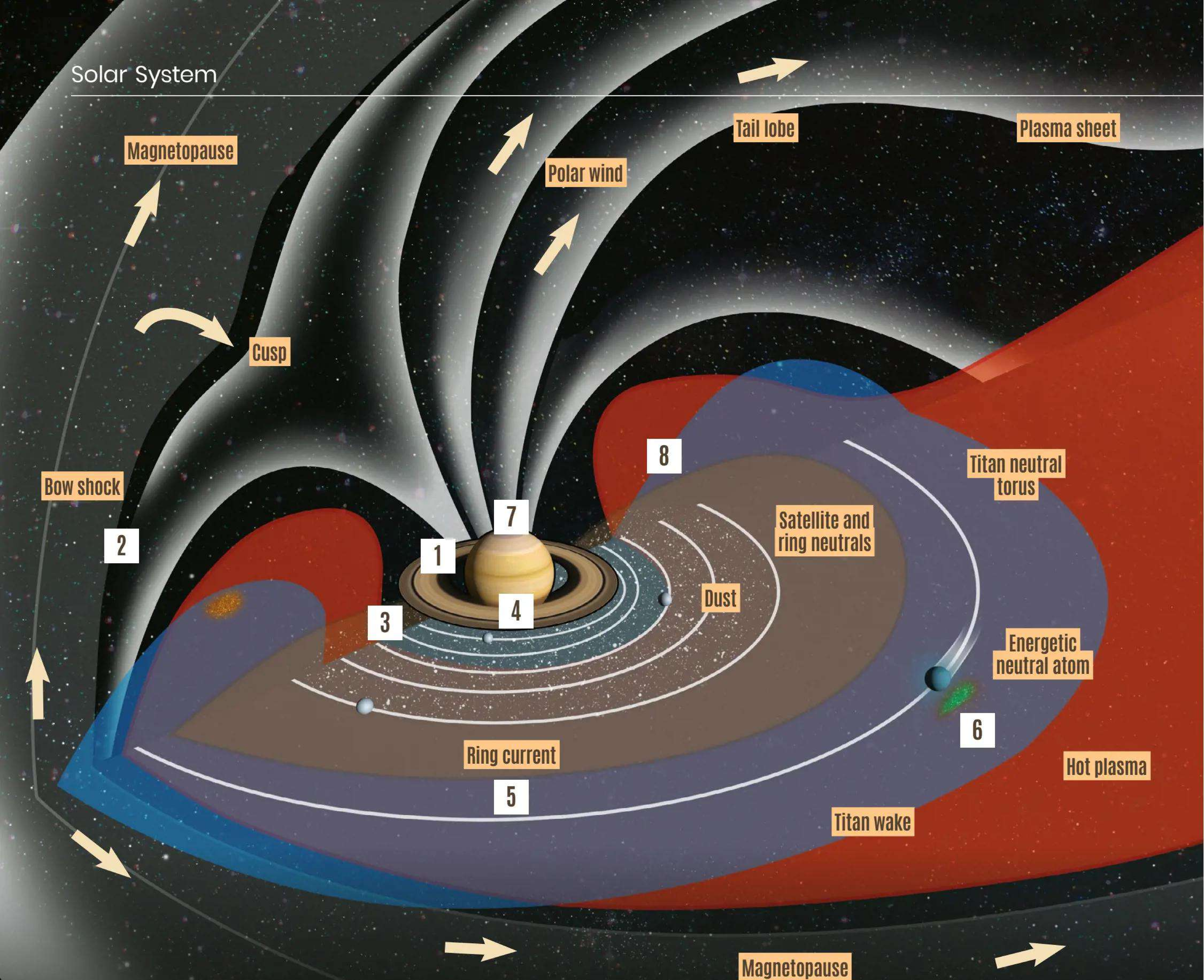
95.16x
Saturn's mass in terms of Earth

61.6 kilograms per cubic metre
Saturn's average density – just over two-thirds that of water

9.05 to 10.12 AU
Distance from the Sun in astronomical units

1.1%
Heating power of the Sun at Saturn compared to Earth

-178°C
The average temperature at Saturn's cloud tops



THE DEEP INTERIOR AND MAGNETOSPHERE

About 9,000 kilometres (5,600 miles) below the visible surface, pressures from the overlying atmosphere become strong enough that hydrogen molecules condense from gas into liquid, creating a vast global ocean that accounts for the bulk of Saturn's interior volume. Deeper inside the planet, hydrogen molecules break down further to create a layer of liquid metallic hydrogen, within which helium forms dense 'raindrops' that fall inwards and help generate the planet's internal heat.

The density of Saturn's interior can be measured through the influence of gravity on spacecraft and structures in the planet's rings. Studies suggest that beneath the liquid-metallic layer sits a concentrated core of rock and ice with a mass of up to 18 Earths – a distinct contrast to the 'fuzzy' deep interior of Jupiter. As Saturn's metallic-hydrogen ocean spins, it carries enormous electric currents that generate a powerful magnetic field. This field is the most organised and symmetrical in the entire Solar System, erupting almost precisely at Saturn's north pole, wrapping around the planet and re-entering at the south pole. The result is an extensive magnetosphere that extends to the orbit of the giant moon Titan on Saturn's sunward side – where it meets and is overwhelmed by the solar magnetic field – and streams away into space in a long 'magnetotail' on the opposite side.

> "Deeper inside the planet, hydrogen molecules break down further to create a layer of liquid metallic hydrogen"

1 Axial alignment
Cassini's measurements confirmed that Saturn's magnetic field is curiously well aligned to its axis of rotation.

2 Shaped by the Sun
Saturn's magnetosphere is sculpted into a teardrop shape by interactions with the Sun's magnetic field and the solar wind.

3 Radiation belts
Weak radiation belts lie just inside and outside the rings; the ring particles and moons tend to soak up the energetic particles that would otherwise create more intense belts.

4 Internal generator
The magnetic field is generated by masses of electrically charged fluid rotating inside the planet.

5 Magnetic disc
The outer reaches of the magnetic field are flattened into a disc-like structure with a 'ring current' flowing around it.

6 Shielding Titan
Saturn's giant moon has no intrinsic magnetism of its own, but its atmosphere is protected by an induced magnetic field as it moves through Saturn's magnetosphere.

7 Puzzling rotation
As the magnetosphere is aligned with Saturn's polar axis, it can't be used to measure the planet's rotation. Even after Cassini, we still don't know how fast Saturn's interior spins.

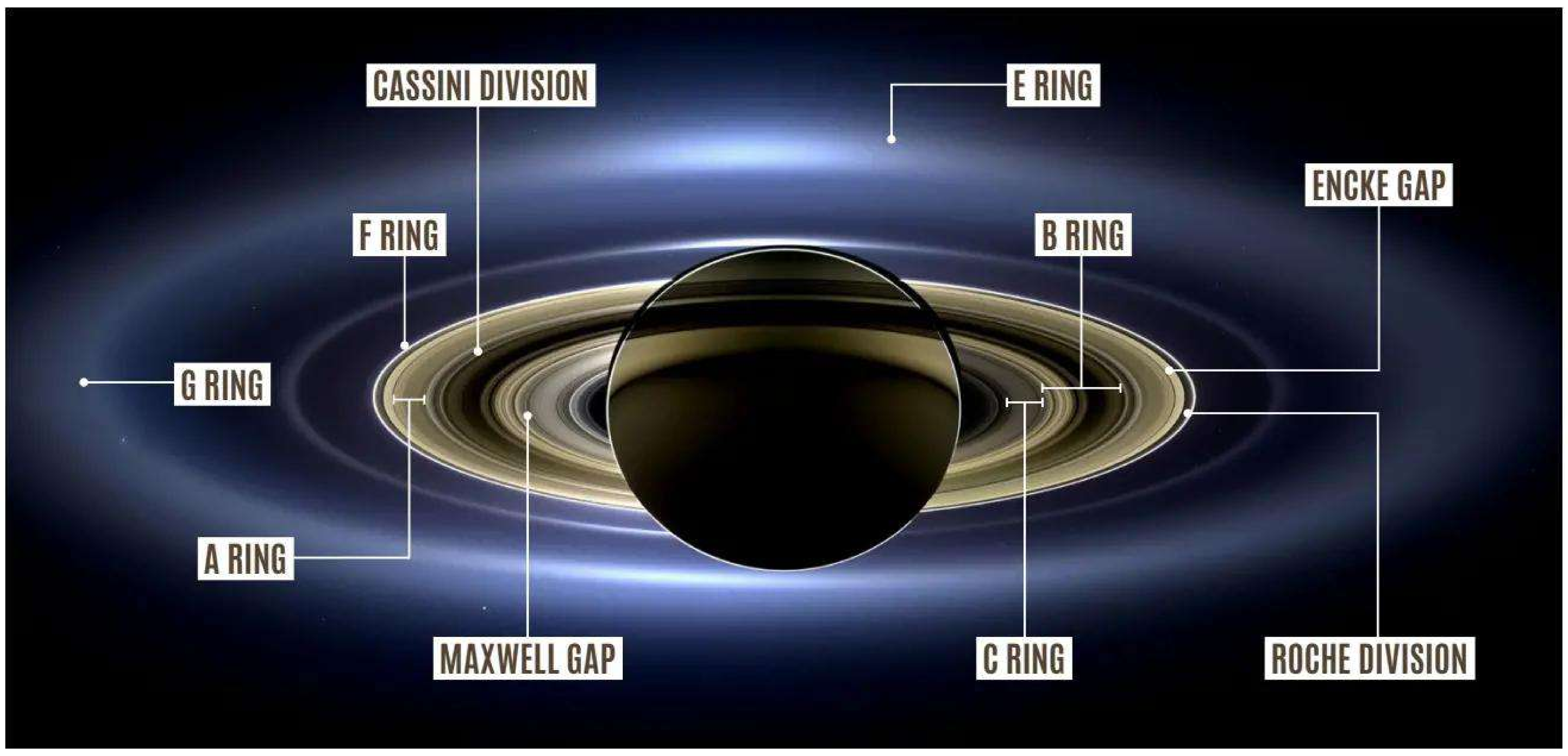
8 Plasma cavity
The magnetosphere is filled with plasma containing electrically charged particles from a variety of sources – mostly water vapour from the moon Enceladus.

LORD OF THE RINGS

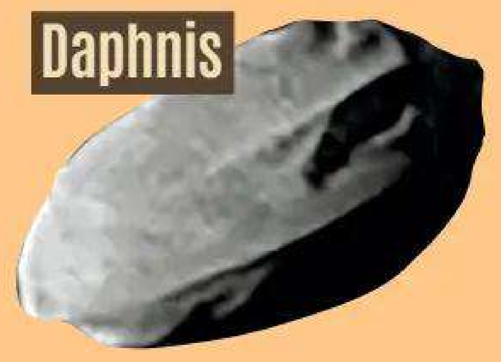
Saturn's bright inner rings extend from about 5,000 kilometres (3,100 miles) to some 76,500 kilometres (47,500 miles) above its cloud tops. From the outside in, the prominent structures are the A and B rings – with B the brightest of all – the C Ring and the near-transparent D Ring. The Cassini Division between the A and B ring is the most obvious of several apparent 'gaps'. Despite their solid appearance, the rings are made from countless particles in independent circular orbits above Saturn's equator. These particles are made almost entirely from bright water ice, so variations in the rings are due to differences in the number and size of particles – ranging from house-sized boulders down to specks of microscopic dust – in different regions. Just beyond the A Ring lies the bright, narrow F ring, while several faint and tenuous outer rings matching the orbits of specific moons are formed from material knocked off their surfaces by micrometeorite impacts – or in the case of the E ring around Enceladus, ejected by geysers. Despite their breadth, the brightest rings are very thin, between one kilometre (0.6 miles) and just ten metres (32.8 feet) thick. Twice in each Saturnian year, as they lie edge-on to Earth, they can disappear completely from view. The next such 'ring plane crossing' will occur in March 2025.

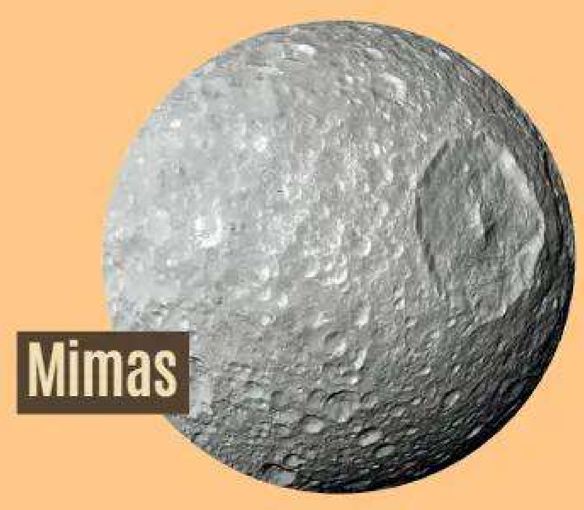
RING DYNAMICS

Ring particles mostly follow circular orbits aligned with Saturn's equator because such orbits keep collisions to a minimum, and the collisions themselves tend to 'damp out' the motion of those which stray out of line. Nevertheless, the rings are in a constant state of change and evolution, largely due to the gravitational influence of Saturn's many moons. Particles in 'resonant' orbits, whose orbital periods are a simple fraction of the period of a more distant moon, can be regularly influenced by that moon's gravity. The effects can be complex, herding particles together in some orbits to create dense, narrow ringlets, and clearing them out of others to create gaps. The narrow F Ring, meanwhile, is governed by a 'shepherd moon' called Prometheus, which orbits near its inner edge and keeps particles tightly confined while also tugging on them to produce intricate twists, knots and braids. Similar effects occur inside the other major rings as particles gently clump together, forming temporary moonlets or propeller-shaped clouds whose weak gravity further shepherds nearby particles. Around Saturn's equinoxes, when the rings lie edge-on to the Sun, short-lived dark features called 'spokes' spread radially across them. They are thought to be a sign of particles being influenced by Saturn's magnetic field.



SATURN'S MOONS





Saturn is the parent of a vast family of satellites, with 146 confirmed as of 2023. The majority are comet-like objects a few kilometres across, captured by Saturn's gravity and orbiting in tilted and eccentric orbits at great distances. Of these 'irregular' moons, the largest by far is Phoebe, a 213-kilometre (132-mile) world that is thought to be a captured centaur – an icy world that probably originated in the Kuiper Belt beyond Neptune. Closer in lie 24 moons with more intimate links to Saturn. Many of these are small moons and moonlets orbiting in and around the rings, but there are eight larger worlds - Mimas, Enceladus, Tethys, Dione, Rhea, Titan, Hyperion and Iapetus – that formed alongside Saturn itself from varied amounts of rock and ice. The largest Saturnian moon of all, Titan, is larger than the planet Mercury and blanketed in a hazy atmosphere of nitrogen and methane. Its surface is shaped by the recycling of methane between icy, liquid and vapour forms, and it may also have active cryovolcanoes.

EXPLORING SATURN

Only a handful of spacecraft have visited Saturn, each adding to our understanding of the ringed planet. Pioneer 11's initial flyby in September 1979 provided the first measurements of the magnetosphere, discovered the F ring and revealed ring material orbiting within the system's apparent dark 'gaps'. Voyager 1 followed in November 1980, delivering high-resolution images of Saturn's atmosphere, rings and moons and measuring the atmospheric gases and high wind speeds. In August 1981, Voyager 2 observed changes in the atmosphere and ring system from the previous year and took the temperature of Saturn's atmosphere for the first time.

However, most of what we know about Saturn today comes from NASA's Cassini mission, which orbited the planet between 2004 and 2017. Still the largest space probe to successfully fulfil its mission, the bus-sized Cassini was equipped with a dozen separate instruments to measure all aspects of Saturn, its rings and moons, as well as carrying the European-built Huygens lander and deploying it for a landing on Titan in January 2005. Observations over more than a decade allowed Cassini to study seasonal changes throughout Saturn's northern winter and spring, culminating with a series of passes between the planet and its inner rings and a final plunge to burn up in the atmosphere in September 2017.

Pioneer 11

Type: Jupiter and Saturn flyby
Launched: 6 April 1973
Saturn flyby: 1 September 1979
Key discoveries: First close-up images of Saturn. Measurements of the magnetic field. Measured the temperature of Titan and photographed the unlit underside of the rings.
Status: Contact lost; now entering interstellar space.

Voyager 1

Type: Jupiter and Saturn flyby
Launched: 5 September 1977
Saturn flyby: 12 November 1980
Key discoveries: Analysis of Saturn's upper atmosphere. Discovery of complex structure in the rings of Saturn. Close-up images of Titan and other moons.
Status: Entered interstellar space in 2012 and is still returning data about its conditions to Earth.

Voyager 2

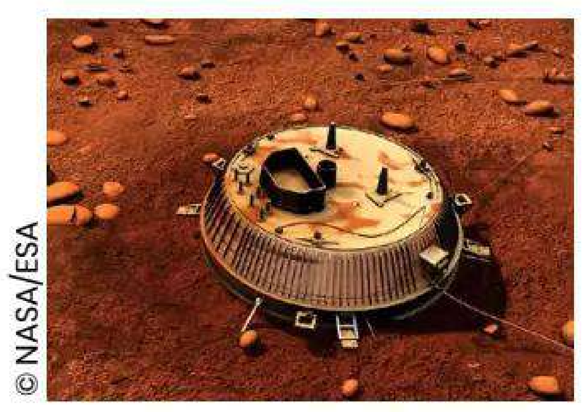
Type: Multi-planet flyby
Launched: 20 August 1977
Saturn flyby: 26 August 1981
Key discoveries: Measurement of temperature in the upper atmosphere. Images of more structure in the rings and the first close-up views of moons, including Enceladus.
Status: Entered interstellar space in 2018; still returning data to Earth.

Cassini

Type: Saturn orbiter
Launched: 15 October 1997
Saturn orbit: 1 July 2004
Key discoveries: Detailed survey of Saturn, its rings and moons. Imaged Titan through its clouds and discovered water plumes above Enceladus.
Status: Destroyed during a controlled plunge into Saturn in September 2017.

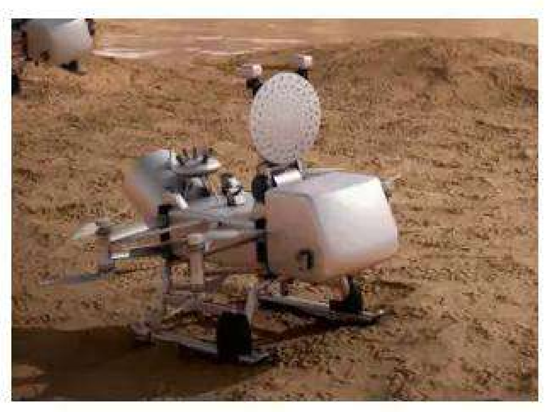
Huygens

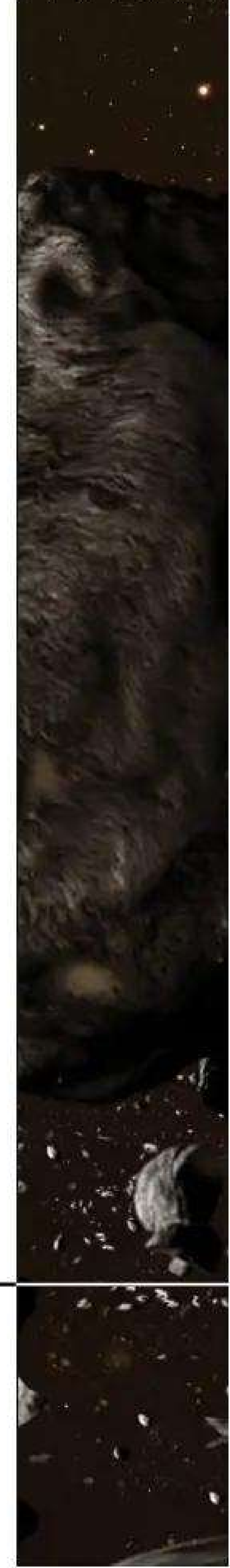
Type: Titan lander
Launched: 15 October 1997
Titan descent: 14 January 2005
Key discoveries: First images from the surface of Titan.
Status: Contact lost with Cassini 72 minutes after landing.

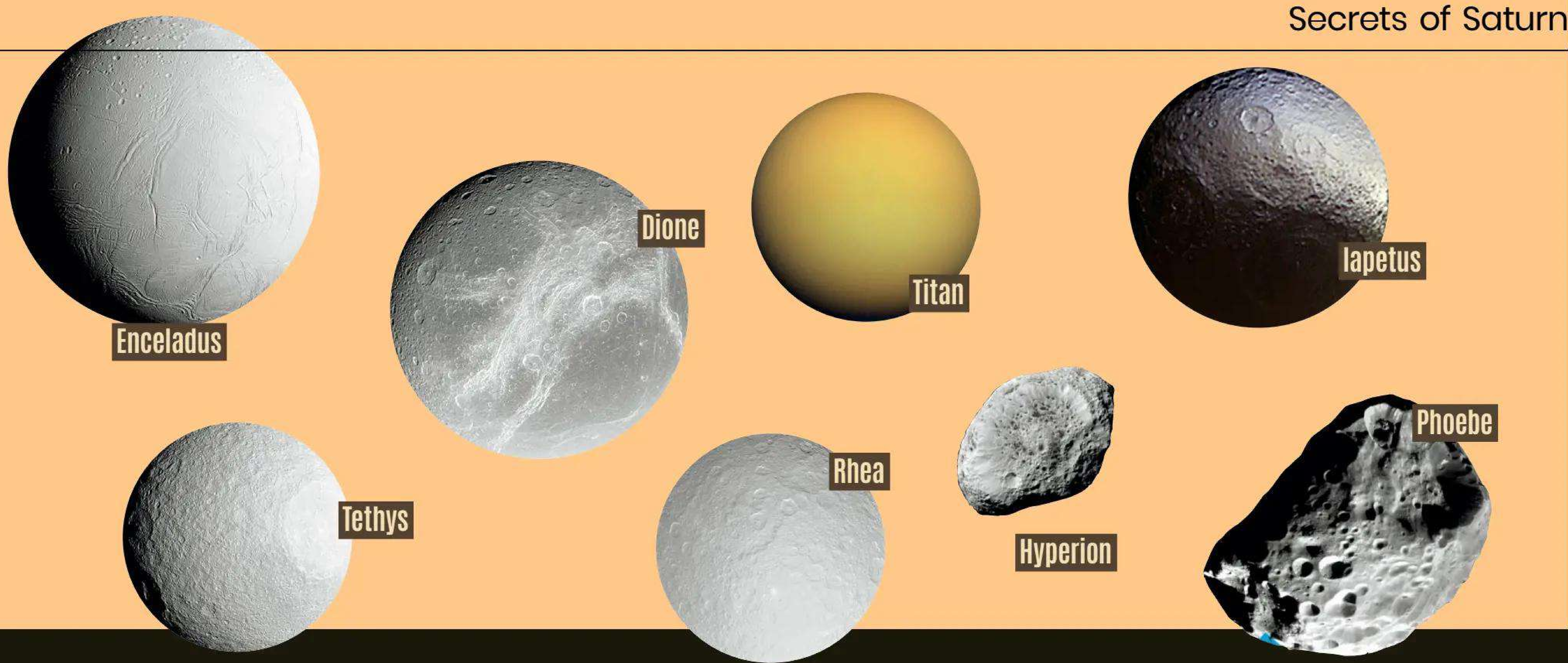


Dragonfly

Type: Titan lander
Launch: 2027
Titan landing: 2034
Key goals: A robotic explorer designed to fly across Titan's surface to several locations, studying the moon's complex surface chemistry and potential for life.







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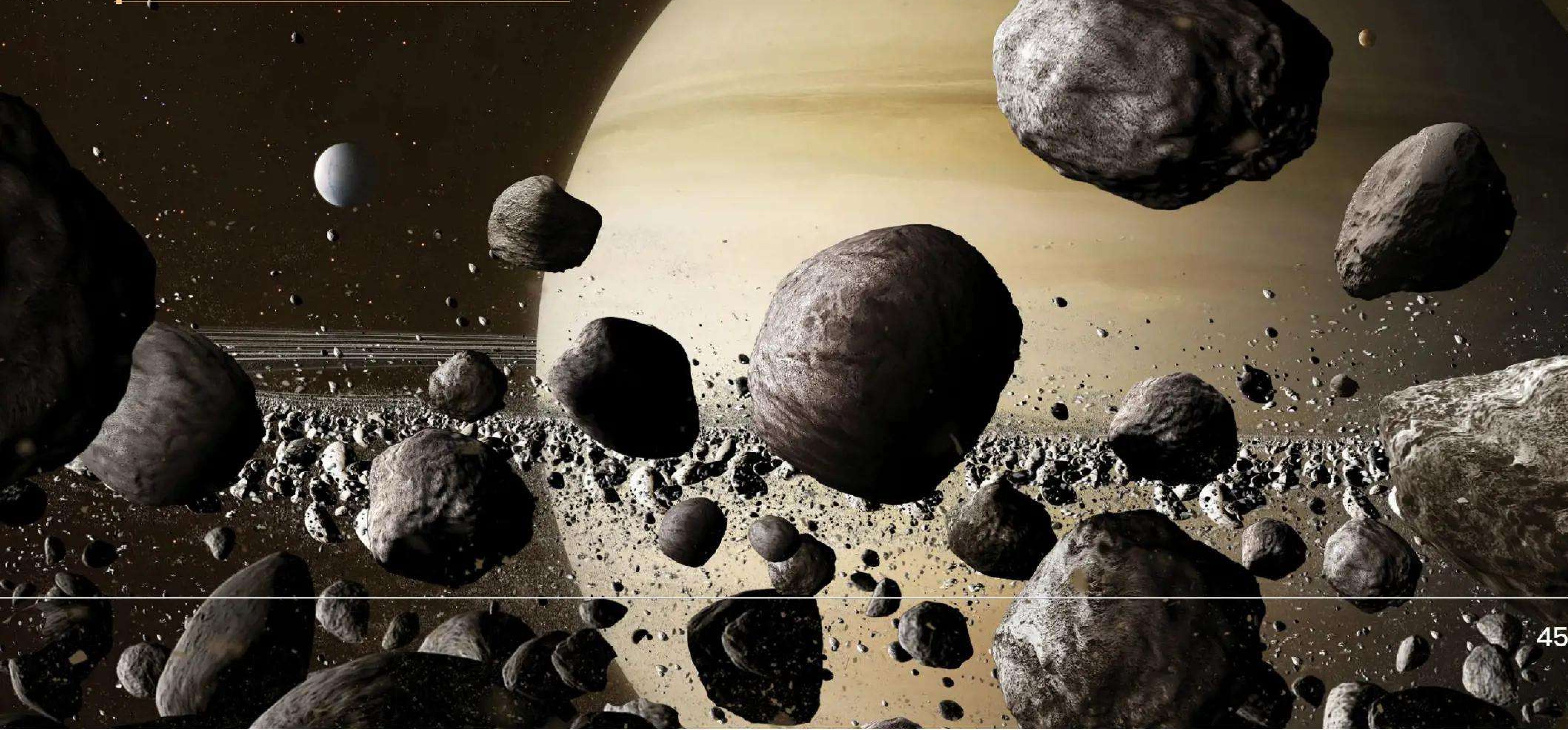
RING AGE AND ORIGINS

The age of Saturn's rings is still hotly debated, though the strongest recent evidence suggests that they are fairly young - perhaps just 100 million years old compared to the 4.5-billion-year age of Saturn itself. The chief evidence for their youth comes from their pristine appearance, coupled with estimates of how fast their particles should darken with age as they are 'polluted' by a steady rain of dusty micrometeorites. However, some scientists argue that the ring particles are rejuvenated by collisions and breakups that expose new surfaces, allowing for a much greater age.

Some advocates for ancient rings suggest they could have formed from a thick disc of material remaining after the planet's own formation. Material far enough from Saturn clumped together to create moons, but within a certain distance called the Roche limit, powerful tidal forces prevented large objects from forming. The leading explanations for a recent ring origin involve the breakup of a lost icy moon, perhaps after its orbit was disrupted by another moon, or in a chance collision with a comet or a second lost moon. This moon or its debris then strayed inside the Roche limit and was further broken up to create the ring particles.

"Some suggest they could have formed from a thick disc of material remaining after the planet's own formation"



FOCUS ON

SATURN'S MOON TITAN MAY NOT BE ABLE TO SUPPORT LIFE AFTER ALL

Titan's ocean has a volume 12 times that of all Earth's oceans, but it may be barren of life as we know it

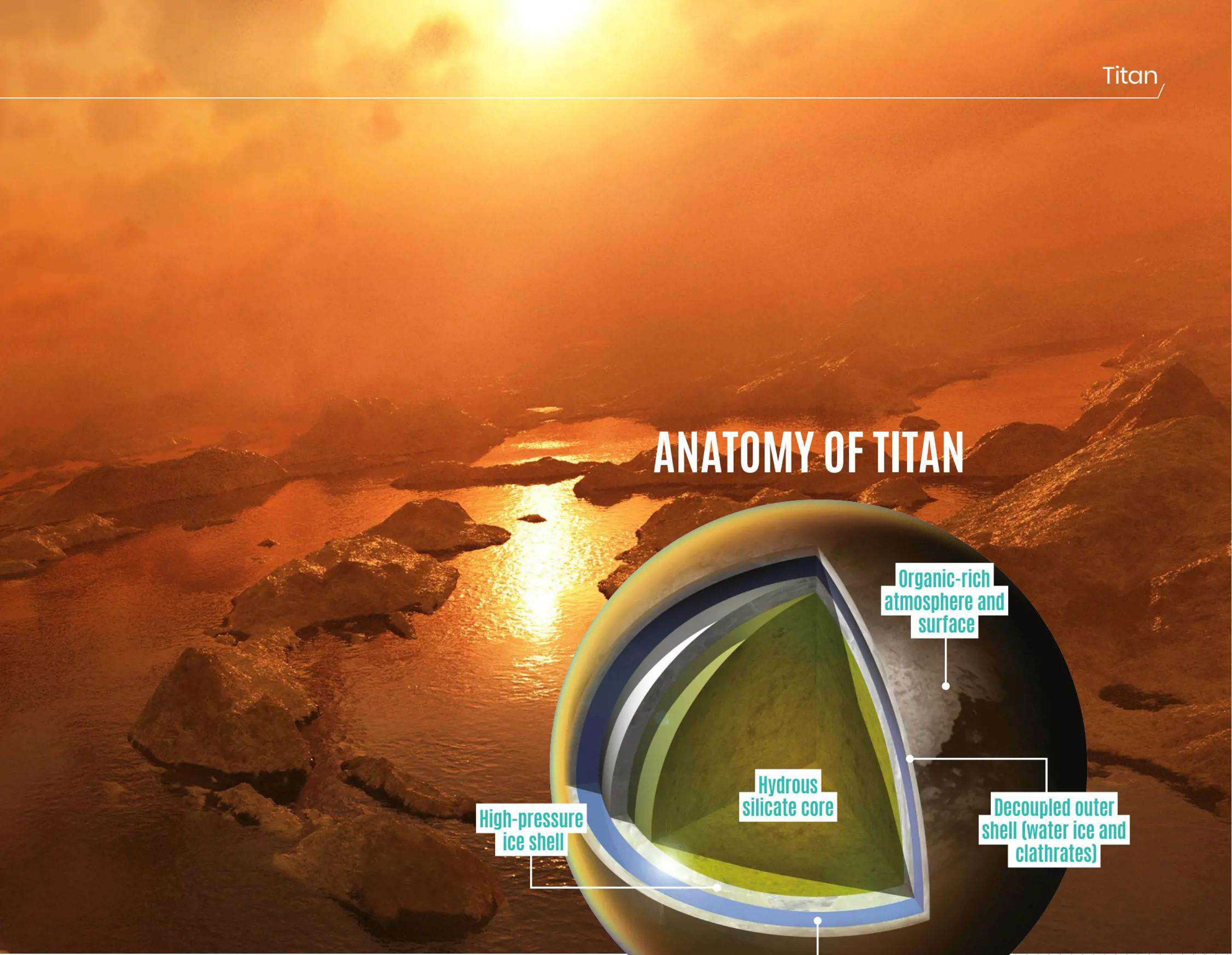
Reported by Keith Cooper

Titan's underground ocean may lack the organic chemistry necessary for life, according to new astrobiological research. Titan is Saturn's largest moon, and the second-largest moon in the entire Solar System. It's famous for being shrouded in a smog of petrochemicals and for possessing a veritable soup of organic molecules – those that contain carbon – on its surface. Yet despite all this fascinating chemistry, Titan is cold. It has surface temperatures no warmer than -179 degrees Celsius (-290 degrees Fahrenheit). And in these frigid conditions, chemical reactions for life progress very slowly.

But deep underground where it's warmer – the exact depth isn't certain, but estimates suggest it's on the order of 100 kilometres (62 miles) – a liquid ocean with a volume 12 times that of Earth's oceans combined is thought to exist. Similar oceans inhabit the interiors of the Saturnian moon Enceladus and Jupiter's moons Europa and Ganymede. And where there's liquid water, there could be life, right? Not so fast, says Catherine Neish of Western University in Ontario, Canada. Neish led an international team that challenged the assumption that Titan's ocean, and indeed the oceans of other icy moons, could be habitable.

The researchers worked on the basis that for Titan's ocean to be habitable, a large supply of organic molecules from the surface must be able to physically reach the ocean in order to facilitate prebiotic chemistry that can produce and feed life. The route for this organic material to reach the ocean is via comet impacts. Such impacts can melt surface ice, creating a pool of liquid water filled with organic molecules. Because liquid water is denser than ice, it sinks. But Neish's modelling found that the rate of impacts isn't high enough for sufficient organic material to reach Titan's ocean.

Neish's team estimates only about 7,500 kilograms of the simplest amino acid, glycine, reaches Titan's ocean every year. It may sound like a lot, but that's equivalent to the mass of one male African elephant spread across an ocean with a dozen times the volume of Earth's oceans... barely a drop in the ocean. "We assumed that the majority of melt deposits – 65 per cent – would sink all the way to the ocean," Neish



said. "Recent modelling work suggests that this is very likely an overestimate, but even in this most optimistic scenario there's not enough organics moving into Titan's ocean to support life there."

There may be other possibilities. On Europa, where there are very few organic molecules on the surface, it's postulated that hydrothermal vents may exist on the seafloor where the ocean comes into contact with the moon's rocky core. These vents would spew all kinds of molecules and trigger complex chemical reactions that could support life. Further evidence for carbon in Europa's ocean has been discovered by the James Webb Space Telescope. Webb identified carbon dioxide that has welled up from the ocean onto Europa's surface. Could the same happen on Titan, with organic material coming from the moon's interior, rather than its surface? Neish doesn't rule it out, saying her colleagues, such as Kelly Miller at the Southwest Research Institute in San Antonio, Texas, are investigating the possibility. But Neish does highlight one particular caveat. "One concern that has come up is whether the organics sourced from the interior would be useful for life," she said. "We think they may be primarily aromatic compounds, and it's difficult to form biomolecules – such as amino acids – from such compounds."

While we are still some ways away from being able to probe the oceans of these icy moons directly to say for certain whether they contain life or not, Neish's research does raise some promising opportunities for NASA's Dragonfly mission to Titan, on which Neish is a co-investigator. Dragonfly is a helicopter mission, inspired in part by the Ingenuity Mars helicopter, which is planned to launch in 2028 for arrival on Titan in 2034. It will explore the moon from the air, touching down to take samples for analysis. If Neish's work is correct, it'd mean there could be many impact sites on the surface where liquid water mixed with organics, possibly sparking some complex chemistry before freezing again and sinking. By studying these sites, scientists could learn more about the prebiotic chemistry that went all the way to forming life on Earth.

FOCUS ON

TRUE-COLOUR IMAGES REVEAL THAT URANUS AND NEPTUNE ARE SIMILAR BLUES

Although the familiar Voyager 2 images of Uranus were published in a form closer to true colour, those of Neptune were stretched and enhanced, making them too blue

Reported by Sharmila Kuthunur

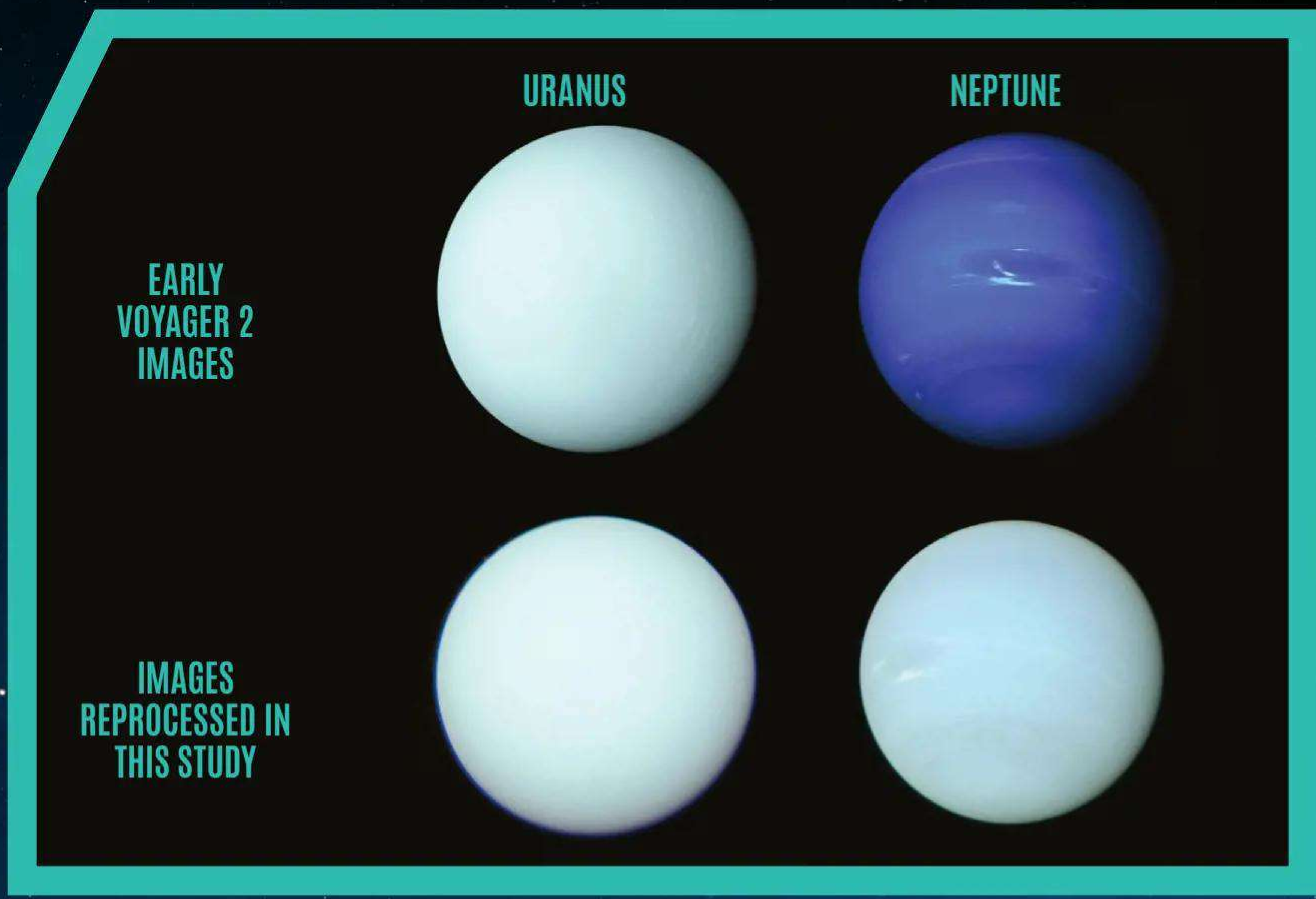
In the summer of 1989, from a remote expanse of our Solar System where sunlight is merely a tepid glow, NASA's Voyager 2 spacecraft radioed to Earth humankind's very first images of Neptune. The pictures revealed the Sun's outermost planet was a stunning deep-blue orb. In contrast, Uranus – Neptune's planetary neighbour and the first to be discovered with a telescope – appeared noticeably paler. Both seemingly twin worlds have a lot in common. They're roughly the same size, almost equally massive and are both enveloped with deep atmospheres made of similar materials. So why were the two orbs different shades of blue? This is a question that has puzzled scientists for decades. Now a fresh analysis of Voyager 2's images shows both ice giants are in fact a similar shade of greenish blue, which is the most accurate representation yet of the planets' colours.

The images Voyager 2 recorded of Uranus and Neptune were in single colours that were combined to create composite images that showed the planets to be cyan and azure respectively. While Uranus' published pictures were processed close to its true colour, early Neptune images had been "stretched and enhanced" to display its clouds, bands and winds, "and therefore made artificially too blue," study lead Patrick Irwin, a planetary physicist at Oxford University said. "Even though the artificially saturated colour was known at the time among planetary scientists – and the images were released with captions explaining it – that distinction had become lost over time."

To resolve the misconception, Irwin and his colleagues used new images from NASA's Hubble Space Telescope and the European Space Agency's Very Large Telescope, whose instruments capture a rich spectrum of colours in each pixel. Processing them determined the true apparent colours of Uranus and Neptune. Next, the team revisited Voyager 2's images and rebalanced them in line with the new data, showing both planets are actually similar shades of blue. The colour comes from a layer of methane in the planets' atmospheres, which absorbs red from the Sun's light.

Uranus is slightly whiter, the new study finds, possibly because its somewhat "stagnant, sluggish" atmosphere permits the methane haze to accumulate, which reflects red portions of sunlight to a greater extent than Neptune does. The presence of amassed methane ice particles may also explain why Uranus changes its colour slightly during its

84-year orbit around the Sun. Images recorded between 1950 and 2016 by the Lowell Observatory in Arizona show the planet appears greener during its solstices – when one of its poles points towards the Sun – and bluer during equinoxes, when the Sun shines directly above its equator. By comparing the brightness of Uranus' poles to its equatorial regions in these images, Irwin and his team concluded methane is likely half as abundant near the poles than at the equator, which accounts for the changing colours. "The misperception of Neptune's colour, as well as the unusual colour changes of Uranus, have bedevilled us for decades," said Heidi Hammel of the Association of Universities for Research in Astronomy, who is not affiliated with the new study. "This comprehensive study should finally put both issues to rest."



Images of Neptune were stretched and enhanced, made to look bluer like this artist's impression

BEYOND PLUTO

From Planet X to objects frozen in time – what truly lurks outside the Solar System's chaotic frontier

Reported by James Romero

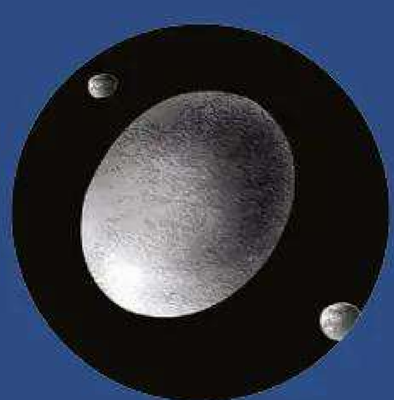
"Like an archaeological dig into the history of our Solar System." That's how New Horizons principal investigator Howard Stern described the spacecraft's mission to Pluto and the outer Solar System. In recent decades, our ability to peer into the murky edges of the Solar System and map the populations of icy bodies that reside there has not only changed our understanding of the true scale and nature of the Solar System, but has also shone a light on the past, revealing how the current arrangement of rocky and icy worlds came to be and how interactions with the wider galaxy might shape its future.

Residents of the outer Solar System can be divided into various populations by their current orbits, history of orbital interactions or their compositional make-up. Kuiper Belt objects (KBOs) are the first population encountered as you move beyond the orbit of Neptune at around 30 astronomical units (AU) – one AU is the Earth-Sun distance. This sparsely populated ring extends out to 2,000 AU and includes icy bodies left over from the formation of the Solar System. Larger residents include Pluto, as well as Eris, Makemake and Haumea, which along with many much smaller inhabitants form a large subgroup known as 'hot' Kuiper belt objects.

Hot KBOs owe their current positions to an ancient eviction of between 10 and 30 Earth masses worth of small bodies from the Solar System's inner regions, likely caused by ancient jostling of young gas

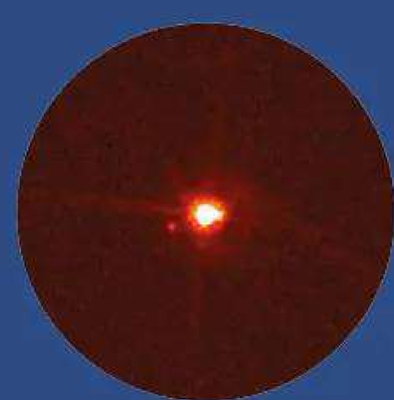
> **"Outside of the Kuiper Belt and hypothetical Oort Cloud, there's a population of bodies fitting neither category"**

WORLDS BEYOND PLUTO



Haumea
Haumea's unusual combination of rings and moons is yet to be explained.

Farfarout
In 2021, Farfarout was confirmed to be the most distant object ever observed in our Solar System.



Eris
Initially thought to be larger than Pluto, Eris' discovery helped end Pluto's planetary status.

Arrokoth
Arrokoth is the most distant object ever explored by a spacecraft.

Makemake
Its reddish hue is due to its surface composition of methane, ethane and possibly nitrogen ices.

and ice giants. This violent event is still evident in hot KBOs' eccentric orbits, often at significant angles from the general plane of the Solar System.

One significant source of insight on the Kuiper Belt, and Pluto in particular, has been the New Horizons mission. After leaving the former planet, the mission team utilised artificial intelligence, in collaboration with data from the Subaru Telescope, to search for the next object to target. The result was a trip to 486958 Arrokoth, a so-called cold KBO. Unlike Pluto and the hot KBO community, Arrokoth is a born and bred Kuiper Belter, forming pretty much in its current location early on in the Solar System's life.

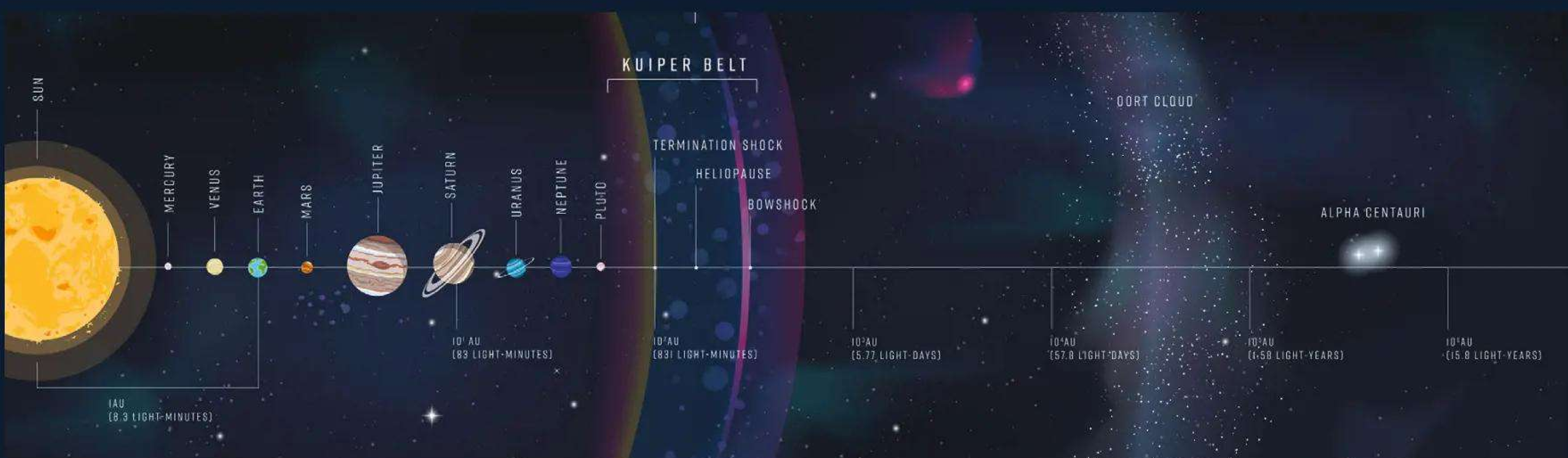
Unlike the geologically active Pluto, with its terrain resurfaced by icy lava, 35-kilometre (21.7-mile) long Arrokoth represents the most primitive body ever observed up close. Its unique peanut shape results from the coming together of two planetesimals, the building blocks of planets, which formed everywhere throughout the early Solar System, but were stunted in their growth in the sparsely populated outer regions. These two lobes, delicately connected by a remarkably narrow neck, provide visual evidence of the stability and undisturbed experience of these ancient relics. And it's this pristine preservation that makes Arrokoth a potential reservoir of information about planetary formation in the early Solar System. "Arrokoth has lived its whole life about where it formed, with minimal impacts or other things happening to it," says Kelsi Singer, deputy project scientist on the mission. "That's why flying by Arrokoth was so revolutionary, because we got to see back in time to how planetesimals formed."

One intriguing aspect of Arrokoth observed by New Horizons is the lack of violent fractures, which you might expect to see if these two lobes once smashed into one another. This suggests that gentle coalescence might be a more potent mechanism for planetary formation. With the exception of Arrokoth and the belt's larger residents, much of the remaining Kuiper Belt population are little more than points of light to astronomers, identified

"Flying by Arrokoth was so revolutionary because we got to see back in time to how planetesimals formed"

Kelsi Singer

- Pluto is the largest and most massive member of the Kuiper Belt
- Jupiter's trojan asteroids are thought to be the inner Solar System cousins of scattered Kuiper Belt objects
- There's evidence that Saturn's moon Phoebe may be a captured centaur from the outer Solar System



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MAPPING THE OUTER SOLAR SYSTEM

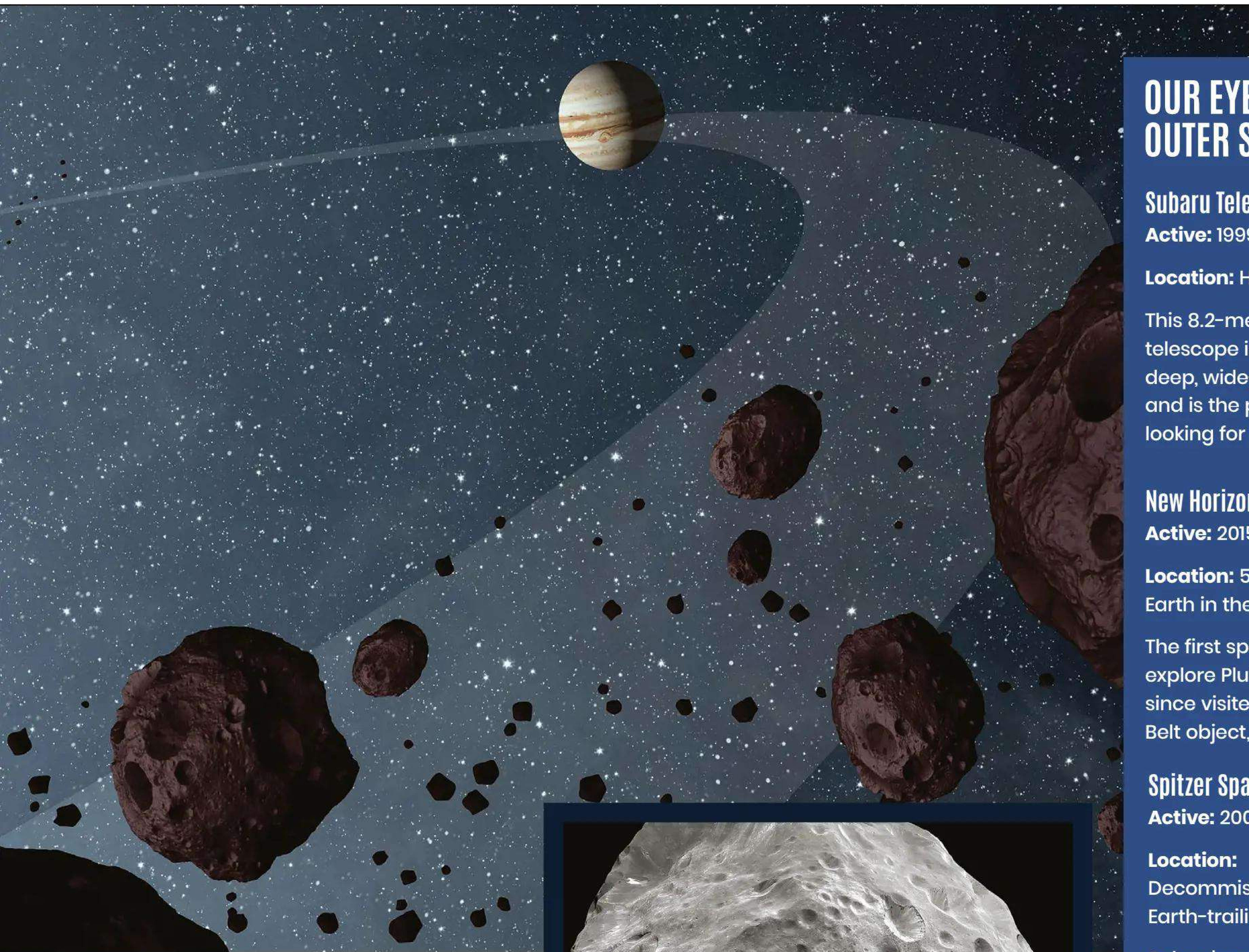
Heliosphere
0 to 122 AU
The outermost section of our Sun's atmosphere is a vast, bubble-like region of space that extends outwards.

Kuiper Belt
30 to 1,000 AU
A doughnut-shaped ring of icy objects orbiting around the Sun beyond Neptune's path.

Heliopause
123 AU
A theoretical boundary where the Sun's solar wind is stopped by the interstellar medium.

Interstellar space
From 123 AU
From here on, the Sun's constant flow of material and magnetic field have little to no effect on distant icy bodies.

Oort Cloud
2,000 to 100,000 AU
The most distant region in our Solar System, its residents are beyond the scope of current observatories.



and tracked from Earth by space-based telescopes like Spitzer and a collection of Earth-based observation programs. These will soon be joined by the Vera C. Rubin Observatory, which will perform all-sky surveys from the Southern Hemisphere from around 2024.

However, even this powerful new observatory won't shed much light on the next region on our trip outwards through the Solar System. As we approach a distance 3,000 times further from the Sun than Earth, we enter the mysterious Oort Cloud – the largest, if ultimately theoretical, region of the Solar System. The inner edge of this three-dimensional shell of icy debris is projected to be reached by the Voyager 1 spacecraft in roughly 300 years, while its outer limits could extend a light year in all directions. Within this diffuse, spherical bubble that encapsulates the Kuiper Belt, our Sun and all the inner planets are perhaps 100 billion icy planetesimals.

Too far out and faint to be observed from Earth, our understanding of the Oort Cloud is inferred from its residents that break free and head inwards. These long-period comets include Hale–Bopp, which lit up Earth's skies in the 1990s. Estonian philosopher and astronomer Ernst Öpik was the first to theorise that long-period comets might come from an area at the edge of our Solar System. Dutch astronomer Jan Oort predicted the existence of this cloud of icy bodies in the 1950s, describing a reserve of frosty objects that occasionally get kicked out of their orbits, probably due to gravitational interactions with other Oort Cloud bodies, and end up visiting the inner Solar System.

Other sources of gravitational influence that could turn Oort Cloud residents into long-period comets might come from outside our Solar System. Like the outer regions of the Kuiper Belt, the Oort Cloud is thought to be a region much more in touch with the wider galaxy than the inner Solar System, says Kat Volk, a senior scientist at the Planetary Science Institute. "The changing gravitational potential of the galaxy as the Sun is going around in the Milky Way can change their orbits because they're so weakly bound to the Sun."

In terms of what makes up the Oort Cloud, different simulations of the formation

OUR EYES ON THE OUTER SOLAR SYSTEM

Subaru Telescope

Active: 1999 to present

Location: Hawaii

This 8.2-metre (26.9-foot) telescope is well suited for deep, wide-field sky surveys and is the primary tool for looking for Planet Nine.

New Horizons

Active: 2015 to present

Location: 55 AU from Earth in the Kuiper Belt

The first spacecraft to explore Pluto up close, it has since visited a second Kuiper Belt object, Arrokoth.

Spitzer Space Telescope

Active: 2003 to 2020

Location: Decommissioned in an Earth-trailing orbit

Spitzer's scientific forte was 'the old, cold and dusty', and it observed many Kuiper Belt objects, centaurs and comets.

Vera C. Rubin Observatory

Active: First light expected in 2025

Location: Chile

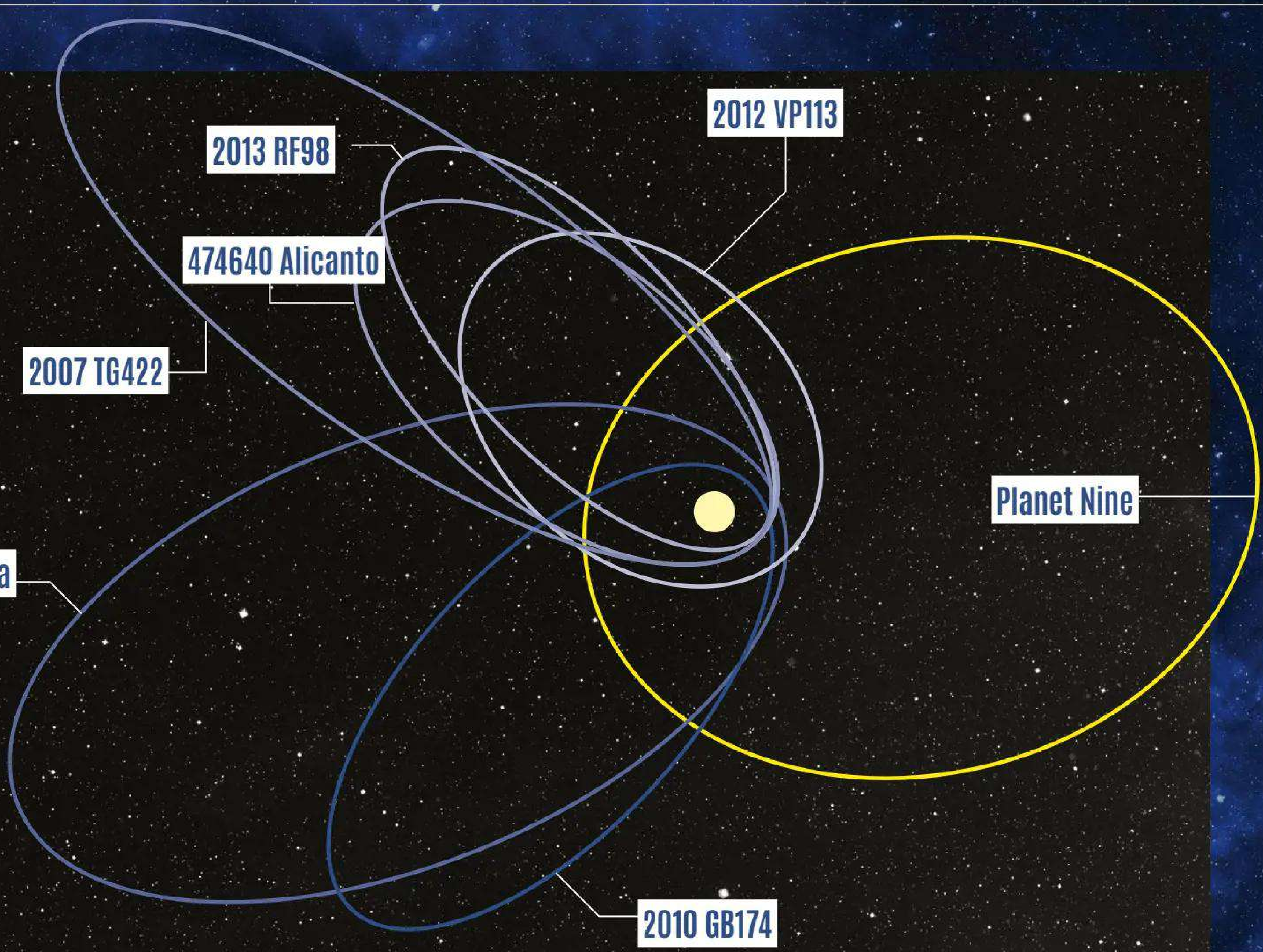
The new observatory aims to increase the number of catalogued Kuiper Belt objects and help with the search for the hypothesised Planet Nine.

James Webb Space Telescope

Active: 2022 to present

Location: Earth-Sun Lagrange point L2

Astronomers hope to use Webb to get information about the surface chemistry of different populations in the Kuiper Belt.



PLANET NINE'S ORBITAL PATH

How we think this world dances around the Sun

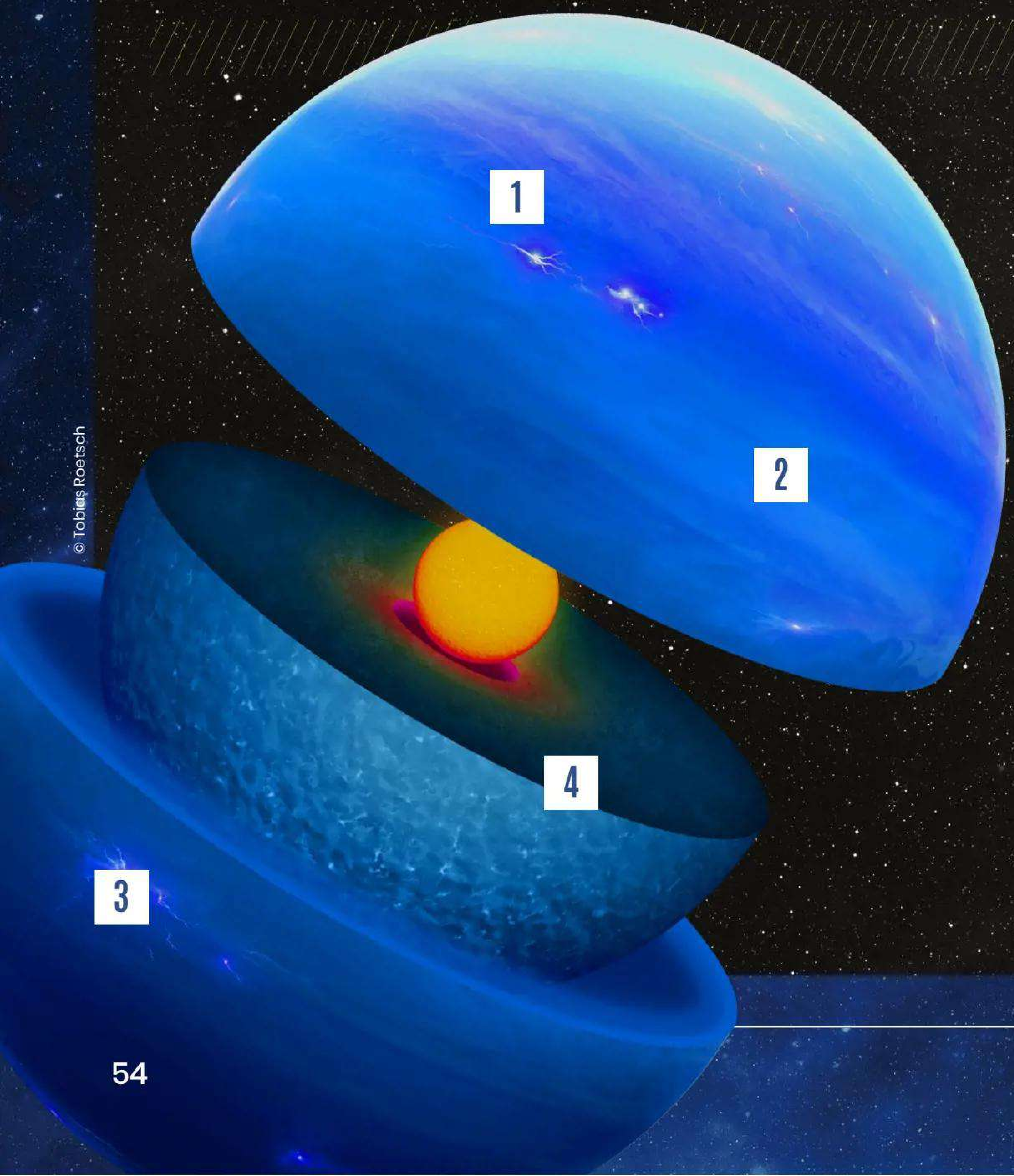
The next nearest planet
Neptune's orbit only takes it out to about 30 AU – more than six times less than the perihelion of Planet Nine.

The inclination
Compared to the other planets in the Solar System, Planet Nine is thought to be inclined by about 30 degrees.

The shape of its orbit
Planet Nine is thought to have a highly eccentric orbit, completing one revolution around the Sun in about 20,000 years.

Closest point
At its closest point to the Sun, known as perihelion, Planet Nine is predicted to approach about 200 AU.

Farthest point
Planet Nine's orbit is thought to extend out to a distance of up to 1,200 AU from the Sun into the far outer Solar System.



WHAT COULD THIS OTHER WORLD BE MADE OF?

Here's what we know about the potential ninth planet

1 Its mass
The planet is thought to have a mass of between 5 and 15 Earths, which could make it a super-Earth type planet.

2 Cold as ice
Being located beyond the orbit of Neptune, it's likely to be extremely cold – any water the planet has will be frozen as ice.

3 On the surface
If the planet is smaller than 1.6 Earth radii it might have a rocky surface. If it's larger, it could be more similar to a gas giant.

4 Inside the planet
As we don't know the planet's radius, we can't yet tell what its core, mantle or atmosphere – if it has one – look like.

of our Solar System predict different origins. Some astronomers have suggested most residents are broadly similar to the hot Kuiper Belt community – objects expelled by the giant inner planets during their formation. But others, like the Southwest Research Institute's Hal Levison, believe a significant proportion of the Oort Cloud population might have been captured from the backyards of a thousand or so star systems that were much closer to us when our Sun was born.

Outside of the Kuiper Belt and hypothetical Oort Cloud, there's a population of bodies fitting neither category. Centaurs are a collection of small bodies whose orbits, at their closest approach to the Sun, position them between Jupiter and Neptune. However, they then swing out beyond Pluto and well into the heart of the Kuiper Belt. In 2019, the most distant object ever discovered in the Solar System turned out to be a centaur. The appropriately nicknamed Farfarout was discovered by Scott Sheppard of the Carnegie Institution for Science and Chad Trujillo of Northern Arizona University using Subaru Telescope data. This distant world orbits the Sun every millennium at a maximum distance of 19.8 billion kilometres (12.3 billion miles). Despite its notoriety, Farfarout wasn't the ultimate aim of Sheppard and Trujillo's outer Solar System surveying. The object they were gathering evidence on was something far larger than had first been predicted a few years before.

In 2016, Mike Brown and Konstantin Batygin, both of the California Institute of Technology, announced evidence that the outer Solar System contained an undiscovered large body, which they dubbed 'Planet Nine'. Brown and Batygin used perceived asymmetry in the orbital alignment of extreme outer Solar System bodies as evidence of the gravitational influence of an unobserved world with a mass 6.2 times Earth's, orbiting between 300 and 380 AU. Brown and Batygin's idea wasn't completely out there. The 'Five-planet Nice model' of the early Solar System, proposed in 2011 by the Southwest Research Institute's David Nesvorný, explains the current locations of the gas and ice giants through the ejection of a fifth giant planet. However, data from the Wide-field Infrared Survey Explorer (WISE) has shown there's nothing Saturn-sized or bigger within a couple thousand AU of the Sun, as the infrared survey would have picked up the remaining planetary heat.

Volk, who proposed an ejected tenth planet of her own a few years later based on perceived torquing of the average orbital planes of some outer Solar System bodies, believes the evidence for both these hypothetical worlds has gotten weaker

DEBATE: IS IT LIKELY THAT ANOTHER PLANET EXISTS?

Scientists are conflicted about the existence of a ninth Solar System planet

YES

If another world isn't there, you need other theories to explain the anomalous patterns we see. You need a theory to explain why the orbits are aligned together, a theory to explain why objects are out of reach of Neptune and another to explain why some orbits get flipped upside down. Another planet explains all of these anomalies consistently.

Konstantin Batygin, California Institute of Technology

NO

One hypothesis involves the collective gravity of minor planets. These orbit so far away from the Sun that the weak gravity can build up slowly over time and come to dominate their dynamical evolution. They can rearrange their own orbits into a distribution similar to what we observe in the outer Solar System. This predicts there's a disc of minor planets more massive than the Kuiper Belt awaiting discovery.

Ann-Marie Madigan, University of Colorado, Boulder

One of the most watched comets in history, Hale-Bopp originated in the Oort Cloud

"Every time we get a big advancement in observational capabilities, we tend to find a population we didn't know was there before"

Kat Volk

in recent years. This comes as the work of Sheppard, Trujillo and others has added more objects and data points to these orbital plots. Now she is looking to the upcoming Vera C. Rubin Observatory for final confirmation either way. "It might not detect any extra planets, but it will detect so many trans-Neptunian objects that we will put this asymmetry to bed… or not. It will either be confirmed, or there will be enough data to say no."

Despite casting doubt on Planet Nine and her own proposed tenth world, Volk thinks we will find something someday. However, given that only 30 Earth masses of material is believed to have been ejected during the early Solar System reorganisation and the less-than-certain chance of anything ejected being gravitationally retained further out, her money is on something more Mars-sized. "I would be surprised, frankly, if we don't find something pretty decently large in the end."

As New Horizons enters its final few years in the Kuiper Belt with no new viable targets in its reticle, NASA has discussed repurposing the spacecraft to measure space weather and interstellar emissions. For outer Solar System population studies, this marks a return to Earth and near orbit-based searches, where new analytical techniques and machine learning could keep with adding plots to our orbital maps. However, understanding these dots of light as tiny worlds, rather than simply plots on a population graph, is going to require voyages beyond Pluto once again. "There's orders of magnitude more information that you could get about these bodies by visiting them at close range with a spacecraft mission," says Singer. "Obviously a spacecraft would be awesome," agrees Volk. "But realistically that's not going to happen any time soon, as there's really no funding in the latest NASA mission portfolio."

Fortunately, the outer Solar System's tendency to throw dirty snowballs inwards means the journey time to a flyby of an outer Solar System world can be cut down significantly. This was seen with the European Space Agency's Rosetta mission. In 2029 the Comet Interceptor will launch, setting up shop 1.5 million kilometres (93 million miles) from Earth. From there the craft will wait for a cometary visitor from the Oort Cloud to arrive, triggering a flyby manoeuvre. It's these ongoing opportunities for close-up observations of outer Solar System bodies, combined with enhanced Earth-based observation capabilities, which should ensure the exploration of the outer Solar System continues, says Volk – even as New Horizon's days of icy-world flybys come to an end. "Every time we get a big advancement in observational capabilities, we tend to find a population we didn't know was there before."

James Romero
Science writer
James has written for *The Biologist*, *Physics World* and *BBC Science Focus*, among other publications. He specialises in planets, moons and astronomy.

Artist's impression of New Horizons encountering Kuiper Belt object Arrokoth

Artist's impression of Arrokoth

FOCUS ON

ARROKOTH THE 'SPACE SNOWMAN' PROBABLY TASTES LIKE SWEET SOAP

Scientists think the Kuiper Belt object is a sugar world, which would explain its reddish hue

Reported by Sharmila Kuthunur

On New Year's Day 2019, NASA's New Horizons spacecraft radioed to Earth images of the farthest object ever explored: a snowman-shaped primordial object named Arrokoth, one of many frigid residents in the Kuiper Belt that sits beyond Neptune's orbit. The pictures revealed the surface of the two-lobed 34-kilometre (21-mile) wide structure to be rusty red, and this mysterious hue has kept scientists puzzled ever since. Originally, scientists proposed that radiation from the solar wind and galactic cosmic rays, which routinely bombard Arrokoth's surface, somehow converts primitive ices like methanol into organic molecules that give off an ultra-red hue. Details about how this process would work, however, remained unclear.

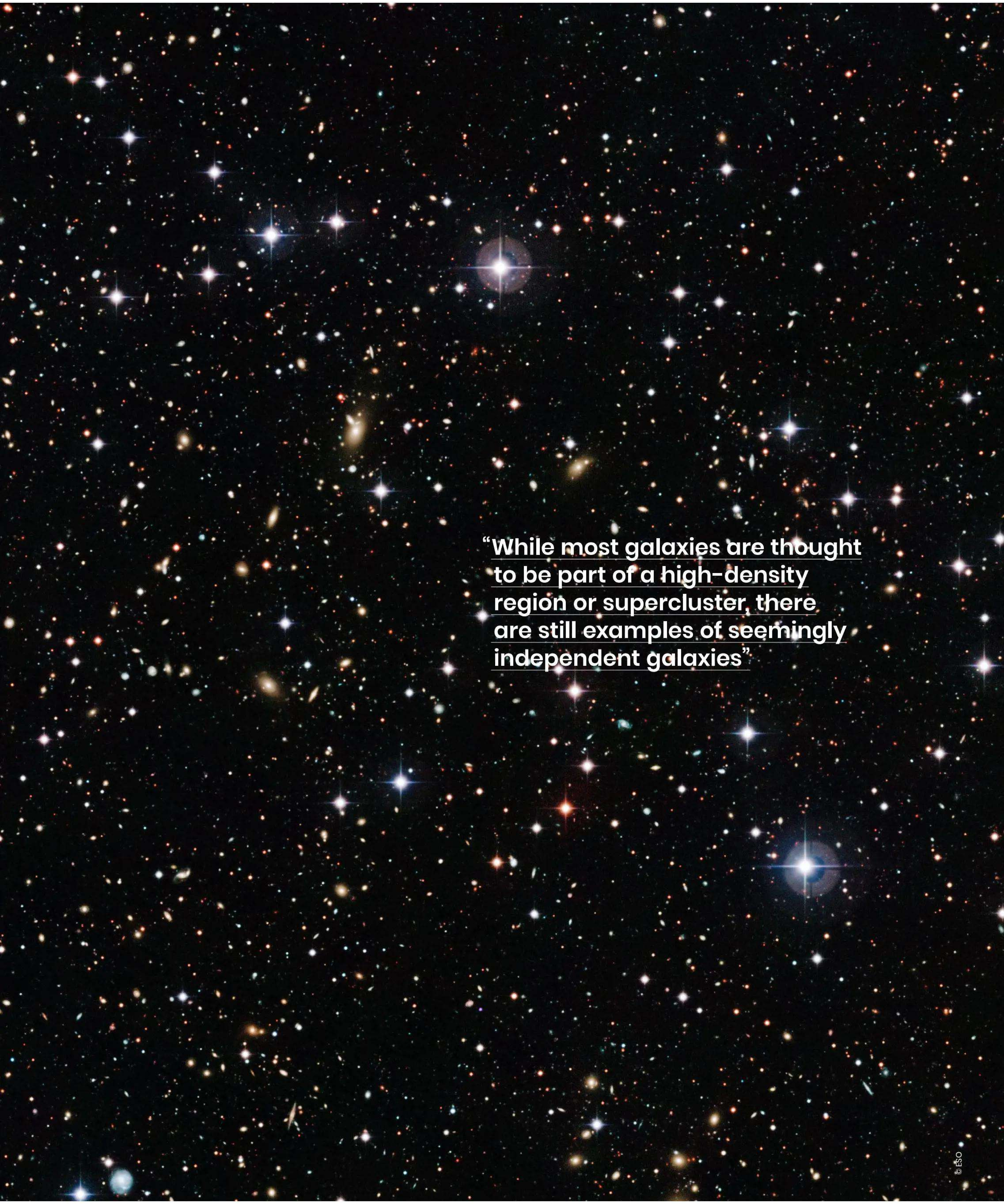
Now we may have some answers. A lab experiment that mimicked space radiation exposure similar to the kind Arrokoth's surface experiences found that a sugar-rich surface may explain the object's distinct red colour. To reach this conclusion, scientists led by Chaojiang Zhang of the University of Hawaii exposed a frozen specimen of methanol and carbon monoxide to high-energy electrons, which served as proxies for the galactic cosmic rays that rain on Arrokoth, at doses equivalent to about 1.8 billion years of space radiation. The simulated radiation set off a series of chemical reactions in the ice, which led to the formation of a group of carbon-rich molecules known as polycyclic aromatic hydrocarbons, or PAHs, known to be common in the universe.

But interestingly, spectroscopic techniques revealed the radiation-infused ices also produced glucose, the main sugar in your blood and your body's primary source of energy. Scientists also detected allose coming out of these experiments, which is a sugar found in fruits and nuts, and glycerol, which is commonly used as a humectant in soaps to help your skin retain its moisture. In other words, Arrokoth probably tastes sweet and soapy.

Moreover, when viewed from space, the PAHs, glucose and other sugars would appear red, the scientists reported. Sugar worlds in the Kuiper Belt may have impacted Earth early in its history and ferried prebiotic molecules, as well as water, to our planet, providing the feedstock for biomolecules that would have been crucial for emerging life.

DEEP SPACE

Go beyond the Solar System and uncover the mysteries of the universe



“While most galaxies are thought to be part of a high-density region or supercluster, there are still examples of seemingly independent galaxies”

© ESO

THE FINAL FRONTIER

Beyond the reach of the Sun is a fascinating region of the cosmos that we're only just beginning to explore

Reported by Robert Lea

The importance of the Sun to our little region of space is immeasurable, providing the light and energy that made life on Earth possible billions of years ago, all the way to the present day. However, our star's influence only extends so far. Beyond the reach of the Sun is a region of the cosmos called interstellar space. Though the first impression of this region may be a cold, empty stretch of space, the truth is that interstellar space is fascinating, exciting and not totally empty.

In many ways, interstellar space represents the 'final frontier' for space exploration, the dream of humanity extending its reach further than its own star and beyond its home planetary system. The distance to interstellar space and the distance to the next star is also a stunning example of how vast the cosmos truly is, highlighting humanity's small place within it. And yet, our species, on a ball of mud and rock around a very average star, has already tested the waters of interstellar space with two active spacecraft.

Launched in 1977, the NASA spacecraft Voyager 1 and 2 left the Solar System in 2012 and 2018 respectively. Since then, the two missions have been collecting data from beyond the influence of the Sun. Voyager 1 is now the furthest human-built object from Earth at a whopping 24 billion kilometres (15 billion miles) away. That's over 161 times the distance between Earth and the Sun, which is around 150 million kilometres (93 million miles) – the basis of a unit of measurement called an astronomical unit, or AU. That means at a distance of around 161 AU, it takes about 20 hours for a signal travelling at light speed to journey between NASA's Voyager team and the Voyager 1 spacecraft.

William Kurth is part of that team, serving as the principal investigator for the Voyager Plasma Wave Science investigation, whose work involves measuring naturally occurring waves in the charged particle environments of space. "Interstellar space is the stuff between the stars and the medium that pervades much of our galaxy. Voyager is making the first direct exploration of what is beyond our star's own environment," Kurth tells **All About Space**. "Specifically with Voyager, we are detecting a spectral feature that is directly related to the number of electrons per unit of volume, or the 'plasma density,' in the interstellar medium beyond the heliosphere, which is the volume of space dominated by the Sun's plasma and magnetic fields."

He adds that plasma density is a fundamental property of various regions of space, and the observations made by the Voyager missions were the first direct measurements of this property in the interstellar medium. The Sun's 'bubble of influence', the heliosphere, surrounds the entire Solar System. Its outer boundary, which marks the beginning of interstellar space, is called the heliopause.

BEYOND THE BORDER

What lies outside the Solar System?

1 Heliopause
This is the boundary of the heliosphere, the bubble around the Sun. The contents of the heliopause are the furthest point from our star to be influenced by its material and its magnetic field.

2 Voyager 1
Launched in 1977 to explore the Solar System's outer planets, Voyager 1 became the first spacecraft to enter interstellar space in August 2012. It's now over 24 billion kilometres (15 miles) away from Earth.

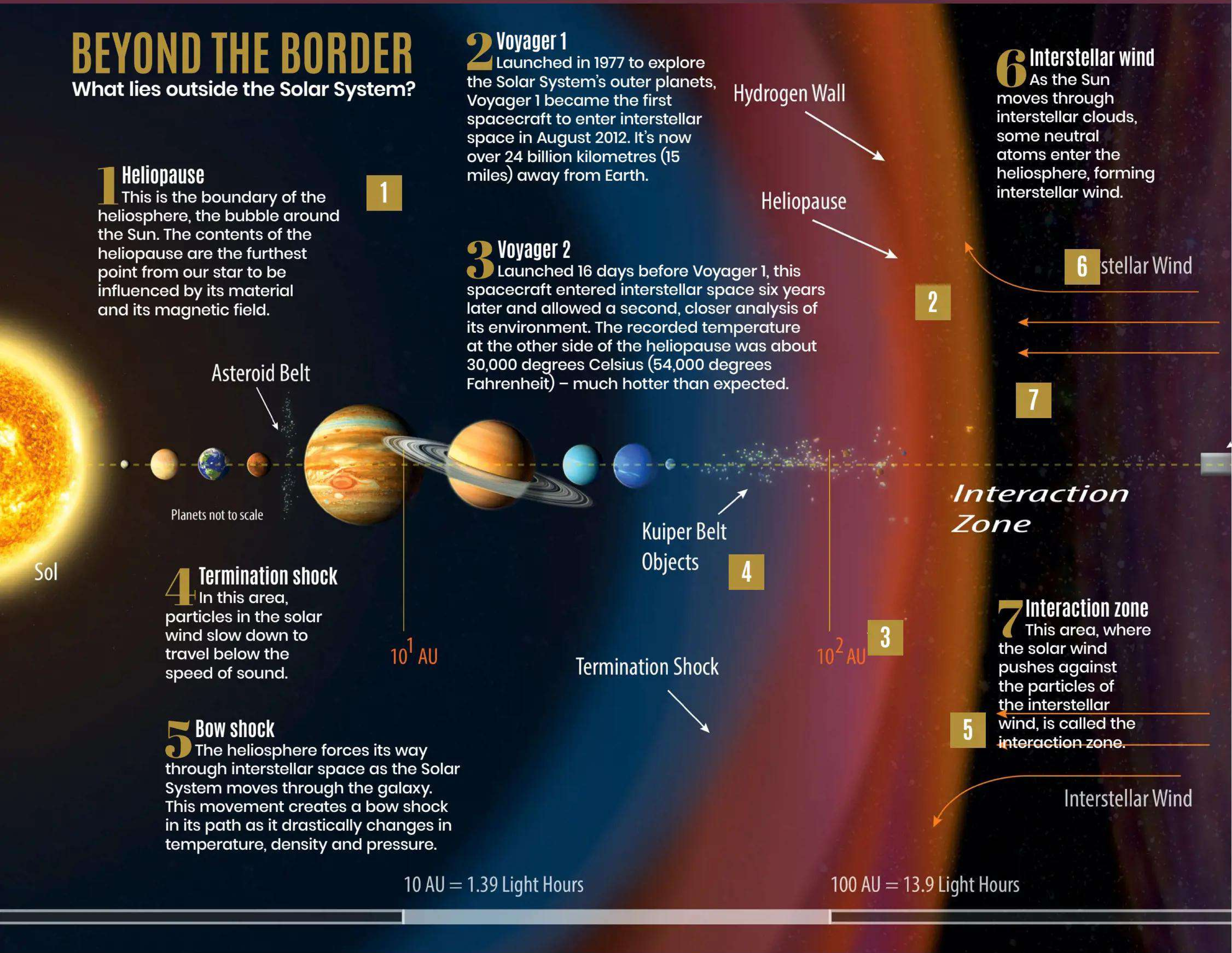
3 Voyager 2
Launched 16 days before Voyager 1, this spacecraft entered interstellar space six years later and allowed a second, closer analysis of its environment. The recorded temperature at the other side of the heliopause was about 30,000 degrees Celsius (54,000 degrees Fahrenheit) – much hotter than expected.

4 Termination shock
In this area, particles in the solar wind slow down to travel below the speed of sound.

5 Bow shock
The heliosphere forces its way through interstellar space as the Solar System moves through the galaxy. This movement creates a bow shock in its path as it drastically changes in temperature, density and pressure.

6 Interstellar wind
As the Sun moves through interstellar clouds, some neutral atoms enter the heliosphere, forming interstellar wind.

7 Interaction zone
This area, where the solar wind pushes against the particles of the interstellar wind, is called the interaction zone.

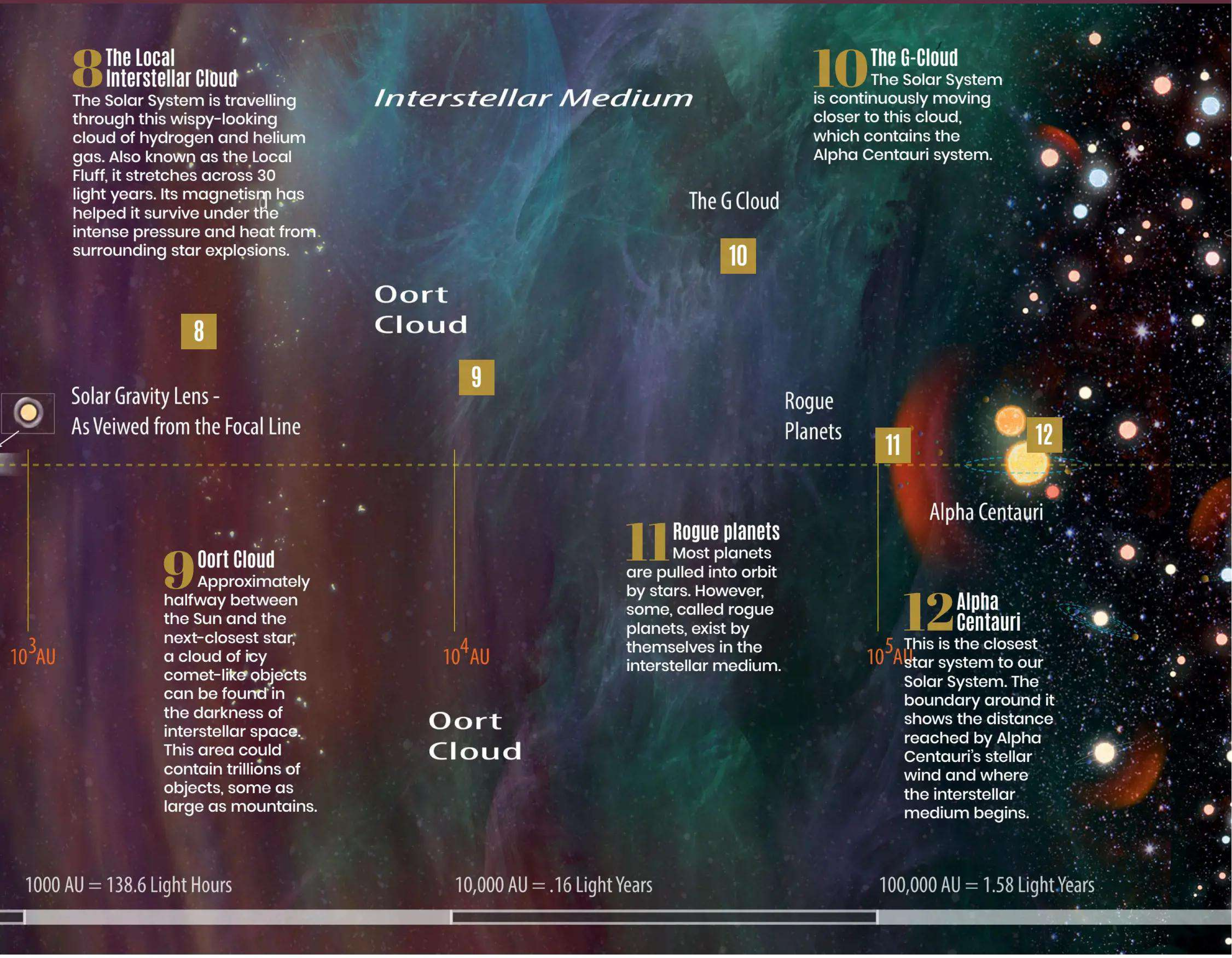


The heliosphere is filled with charged particles that stream from the Sun in what is known as the solar wind. Beyond this is the 'termination shock', where the solar wind meets material from interstellar space, called the interstellar medium. Here, the speed of these charged particles from the Sun is decreased to subsonic speeds of less than 402 kilometres (250 miles) per hour.

The Voyager missions found the heliopause to be located around 120 AU from the Sun, so around 120 times the distance between Earth and our star. The two spacecraft were able to detect the crossing of this boundary by observing an increase in the amount of charged particles from cosmic sources beyond the Solar System and a decrease in solar wind particles. The shape of the heliosphere is determined by the Sun's passage through interstellar space at around 724,200 kilometres (450,000 miles) per hour. The heliosphere was once thought to be teardrop-shaped, but thanks to the Voyager observations and the Cassini spacecraft, scientists now know it to be spherical with a trailing tail.

"Much of what we knew about the interstellar medium before Voyager came from astronomical studies of light from other stars affected by the medium through which it passed," Kurth says. "This is a great tool, but because the stars are

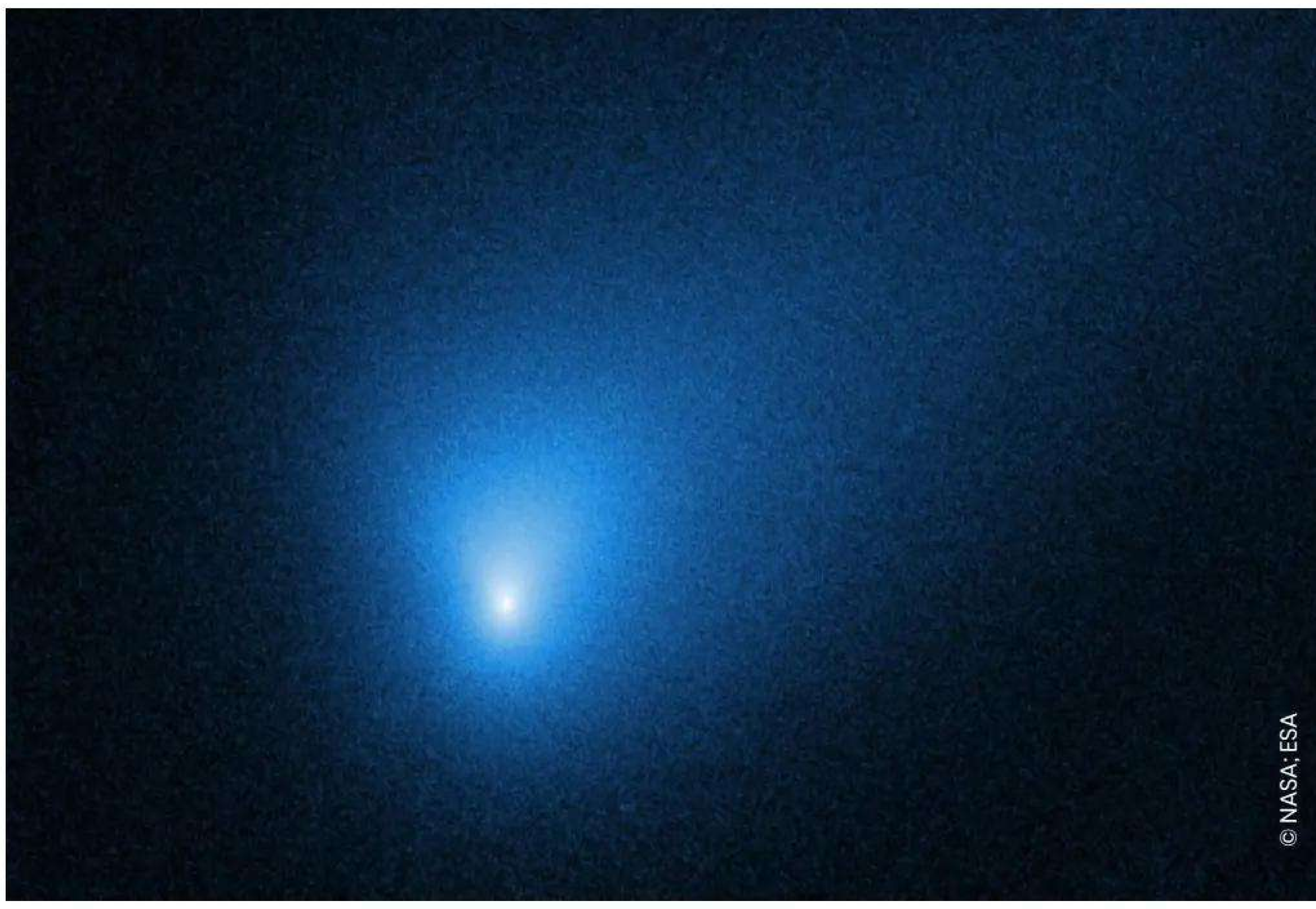
> **"We hope the two Voyagers can continue to make their measurements for several more years" William Kurth**



so distant, those measurements do not pinpoint specific locations, but average, in a sense, across the entire path travelled by the light." He explains that 'in-situ' explorers like Voyager are vital in expanding our understanding of what lies beyond the heliosphere. "The measurements with which I'm involved have shown that the plasma density slowly rises beyond the heliopause to about six electrons in the volume of a golf ball," Kurth says. "That doesn't sound like a lot, but it's 50 to 100 times the plasma density in the farthest reaches of the Sun's atmosphere or the heliosphere."

He adds that Voyager has also measured the flux of charged particles from beyond the Solar System, or 'galactic cosmic rays',

The interstellar intruder 2I/Borisov as imaged on 12 October 2019



before they have been filtered by magnetic fields in the heliosphere. "This filtering is actually critical to life on Earth, as these cosmic rays are extremely energetic and would be a severe threat to life on Earth if they weren't reduced in flux before they made it to Earth," Kurth continues. "We've also observed evidence of the Sun's influence on the nearby interstellar medium."

The outward flow of the solar wind matches and balances the inward push of the interstellar medium. However, beyond the termination shock, where the solar wind and the interstellar medium meet, Voyager found that more violent solar events – like massive eruptions of plasma from the Sun called coronal mass ejections, or CMEs – can make it all the way through the heliosphere over timescales of a year or more and disrupt the local interstellar medium. That means that when the Sun throws a tantrum, its reach can go beyond the heliosphere.

While Voyager 1 and 2 make up the total number of active interstellar explorers, Kurth says that Pioneer 10 and 11 are also likely in interstellar space by now, but ceased operations before they got that far. Contact with Pioneer 10, launched in 1972, was lost in January 2003, and it's now predicted to be around 134 AU away. Contact was lost with Pioneer 11 in November 1995, despite the fact it launched the year after Pioneer 10. It's now estimated to be about 111 AU from Earth. Additionally, many upper stages of launch vehicles are believed to be passing out of the Solar System, and the New Horizons probe is predicted to leave the Solar System and pass Pioneer 11 and 10 in 2143 and 2314 respectively, though this spacecraft will never catch up to the Voyager units. That's

WHAT WE KNOW ABOUT 'OUMUAMUA

While research time was limited, what did we manage to find out?

It's likely wrapped in organic insulation
'Oumuamua is made up of organic ices such as frozen carbon dioxide, methane and methanol. Thanks to long-term exposure to cosmic radiation, a dark-red outer crust some half a metre thick appears to have formed over it.

It's tumbling
Light-curve observations showed 'Oumuamua to have wild swings in brightness, indicating an irregular, excited tumbling motion that's rarely seen in celestial bodies. It spins on its axis every 7.34 hours.

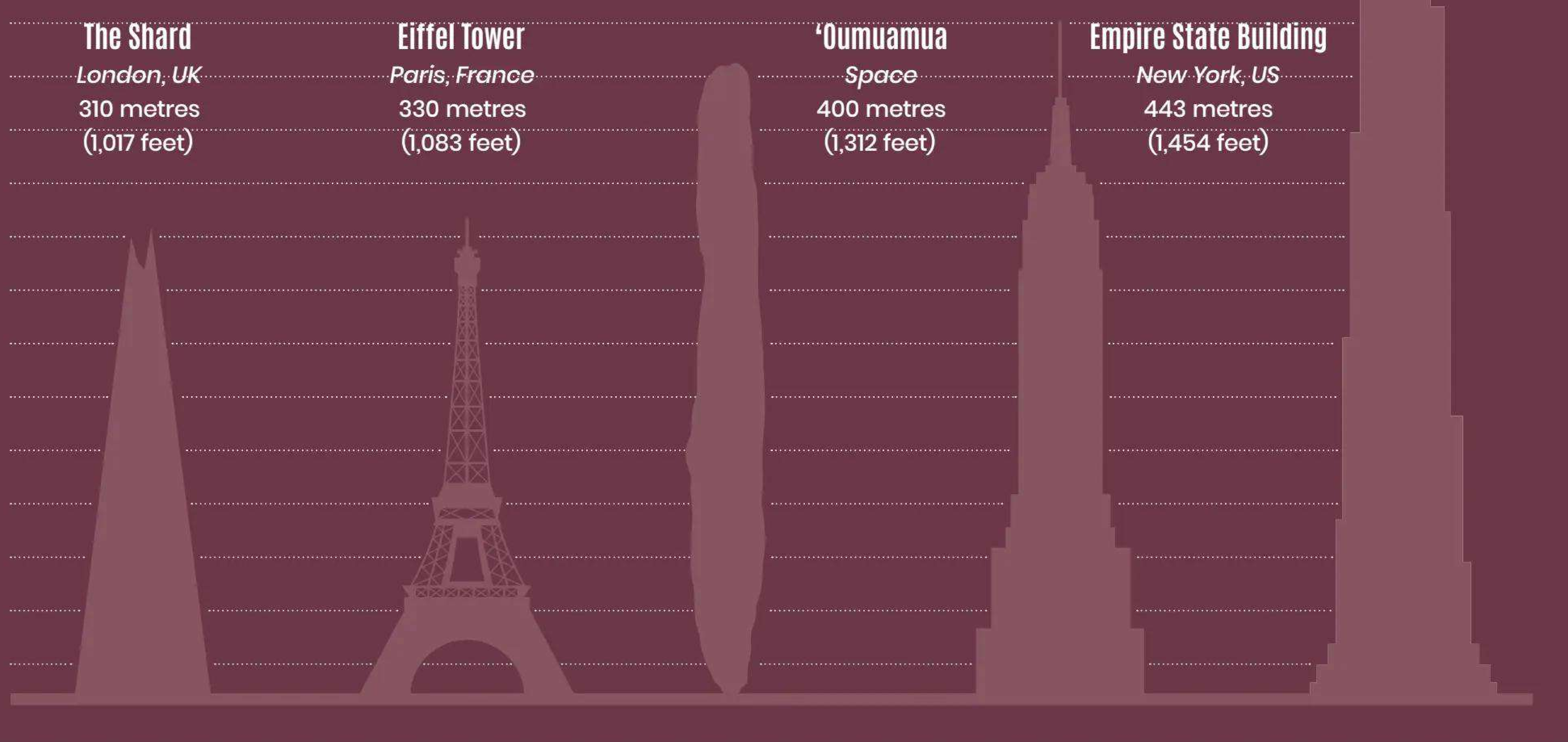
It moves quickly
'Oumuamua was discovered travelling at 87.3 kilometres (54.2 miles) per second. Since it was on its way out of our Solar System when it was discovered, it soon became too faint to see.

It's a natural object
Although there had been suggestions that 'Oumuamua could be an alien-made spacecraft, no directed or broadcast radio transmissions were detected from it when the SETI Institute ran tests.

It's probably not a comet
Even though 'Oumuamua did not have a coma or a tail, it was still initially deemed to be a comet. That was dispelled when astronomers saw no signs of cometary activity, but things can change.

HOW BIG IS 'OUMUAMUA?

How does it compare to human engineering?



"Interstellar space is the stuff between the stars and the medium that pervades much of our galaxy" **William Kurth**

the extent of human-made craft going out of the Solar System and entering interstellar space, but what about objects going the other way?

The first confirmed interstellar invader was discovered by Canadian physicist and astronomer Robert Weryk using the Pan-STARRS telescope at the Haleakalā Observatory in Hawaii on 19 October 2017. Though it was officially designated 1I/2017 U1, the interstellar object became better known as 'Oumuamua, meaning 'a messenger from afar arriving first' in Hawaiian. 'Oumuamua was identified as coming from beyond the Solar System thanks to its incredible speed, moving at 315,430 kilometres (196,000 miles) per hour, whereas asteroids and comets from within the Solar System move at an average speed of just 69,200 kilometres (43,000 miles) per hour.

'Oumuamua is remarkable for more than just its origins. While its red-brown colouration resembles bodies found on the outskirts of the Solar System, its shape is truly alien. Measuring up to 400 metres (1,312 feet) in length, 'Oumuamua is cigar-

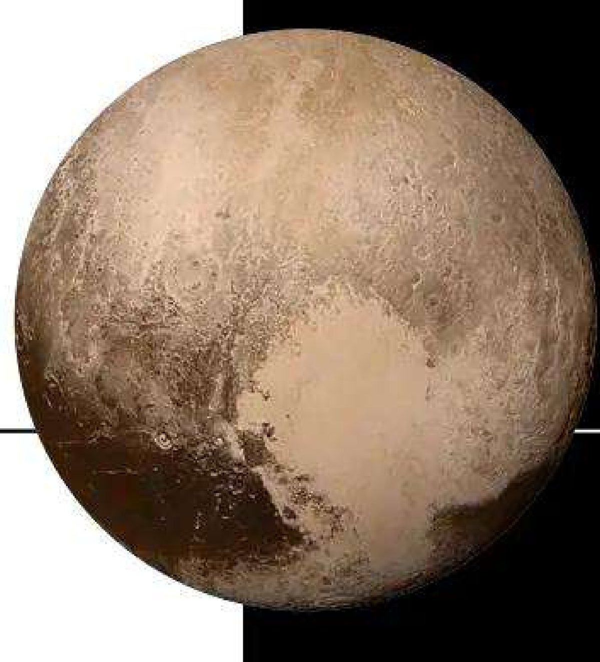
WHERE ARE VOYAGER 1 AND 2 RIGHT NOW?

Voyager 1 launched on 5 September 1977 and is currently around 24 billion kilometres (15 billion miles) from Earth. The first mission of the Voyager program reached the edge of the Solar System and ventured into interstellar space on 25 August 2012. Voyager 2 actually launched before Voyager 1, blasting off on 20 August 1977. It reached interstellar space on 5 November 2018 and is currently an estimated 20 billion kilometres (12.7 billion miles) from Earth.

shaped. Being ten times longer than it is wide makes it like no asteroid or comet yet seen that originates from within the Solar System. While we're on the topic of comets and asteroids, 'Oumuamua was originally classified as the former, but close observations revealed that it lacked the halo and tail of expelled gas that characterises comets approaching the Sun. This would classify it as an asteroid, not a comet, as does the fact it seems to be mostly rock. Yet 'Oumuamua does seem to be expelling some gas, with this contributing to its immense speed, so at the moment 'Oumuamua seems to be a weird hybrid of an asteroid and a comet.

We may never settle the mysteries around 'Oumuamua either. The cigar-shaped space rock isn't sticking around for further study. 'Oumuamua is on a one-way trip out of the Solar System, with the interstellar invader crossing the orbit of Neptune, the furthest major planet from the Sun, in 2022. Observations of 'Oumuamua indicated to astronomers that visitors from interstellar space are fairly common in the Solar System, and they didn't have to wait long for the next one. On 30 August 2019, Crimean amateur astronomer Gennadiy Borisov discovered the second interstellar visitor and the first full comet from beyond the Solar System. The comet was named 2I/Borisov for its discoverer.

The Hubble Space Telescope was able to capture images of 2I/Borisov in October and December of 2019 as it raced through the Solar System at 177,030 kilometres (110,000 miles) per hour – a breakneck speed that once again indicated an interstellar origin. Unlike its predecessor, 2I/



3 December 1973

First spacecraft to Jupiter

1 Pioneer 10 came close enough to the giant planet to acquire a gravitational boost that ensured it would eventually escape from the Solar System into interstellar space.

1 September 1979

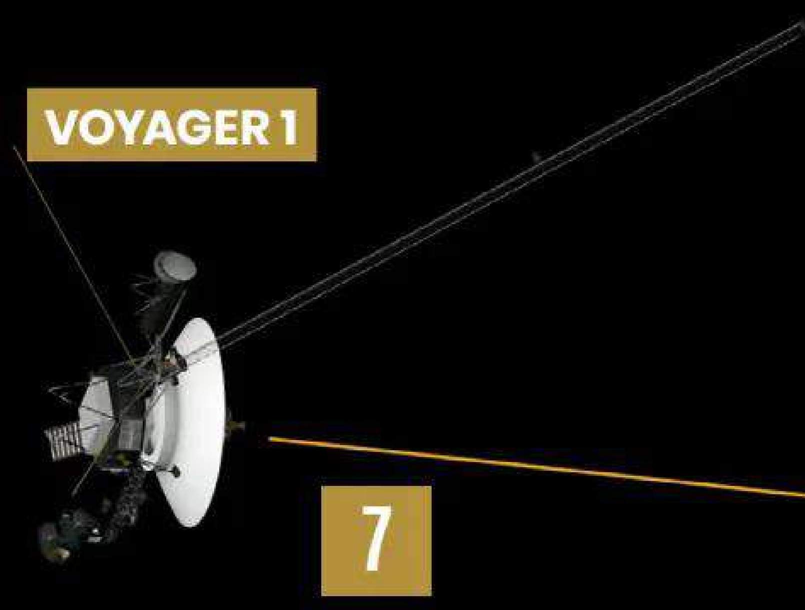
Inside Saturn's rings

2 Pioneer 11 flew past Jupiter too, but it then went on to the next planet out, passing within 20,920 kilometres (13,000 miles) of Saturn – well inside the planet's rings.

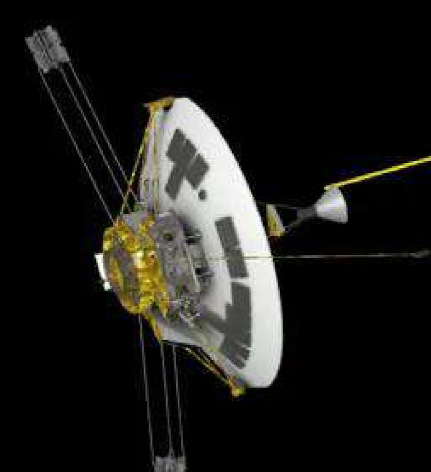
12 November 1980

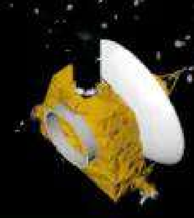
Exploring the Saturnian system

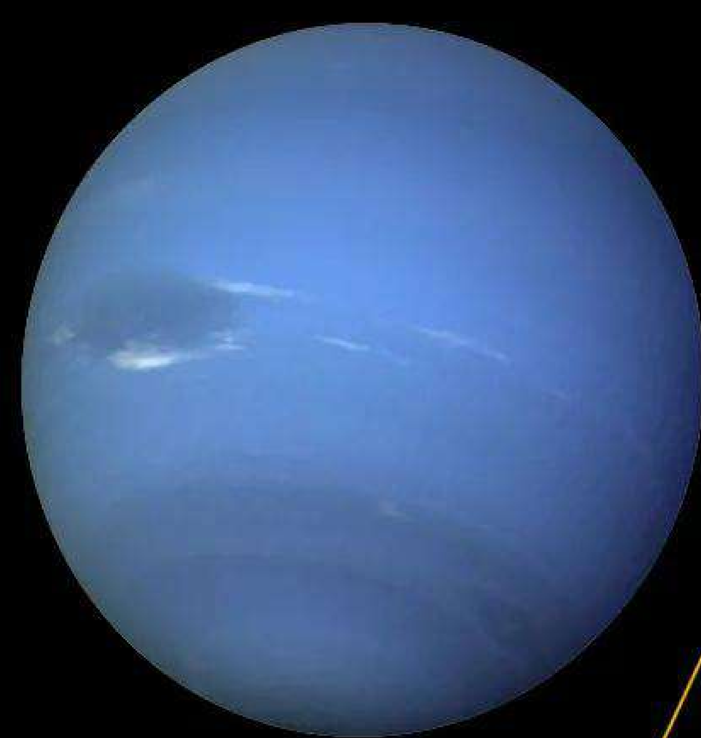
3 Voyager 1 also visited Jupiter and Saturn, but with much more sophisticated instruments than Pioneer 11, taking spectacular close-up images of the ringed planet and its moon Titan.



The rings of Uranus, taken by Voyager 2 on 22 January 1986







DEEP-SPACE PROBES

Before heading out of the Solar System, these five probes achieved some impressive firsts

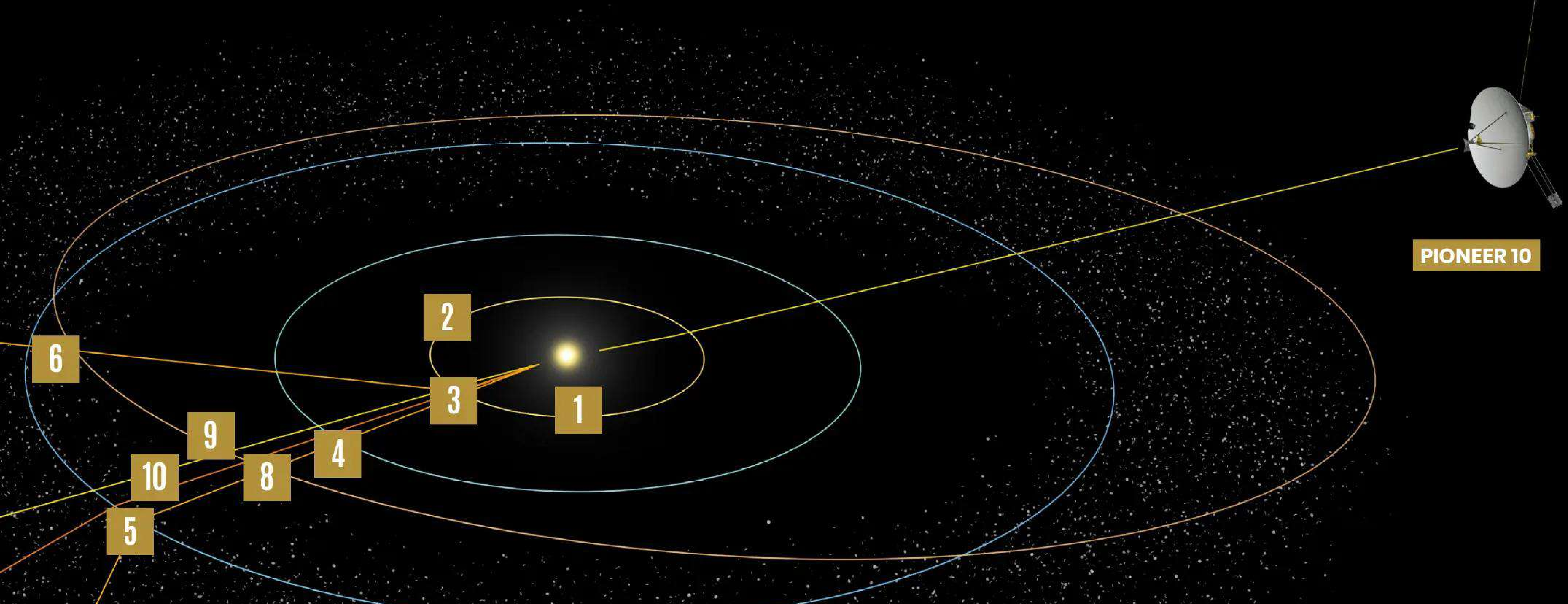
KEY: SATURN, URANUS, NEPTUNE, PLUTO

24 January 1986
The rings of Uranus
4 Voyager 2 was the first probe to reach Uranus, the icy seventh planet, capturing the first clear images of its faint ring system.

25 August 1989
The outermost planet
5 After Uranus, Voyager 2 went on to another ice giant, Neptune – by current definition the Solar System's outermost planet – and discovered five previously unknown moons around it.

14 February 1990
Voyager 1's last photo
6 Just before Voyager 1's camera was switched off, it took one last picture looking back at Earth – the famous 'Pale Blue Dot'.

25 August 2012
Entering interstellar space
7 Voyager 1 became the first spacecraft to cross the heliopause – technically the start of interstellar space. It was followed by Voyager 2 on 5 November 2018.



> "The Voyager craft were designed to last four years, but they've both been operating since 1977" **Kirby Runyon**

14 July 2015
New Horizons at Pluto
8 The closest of the dwarf planets in the Kuiper Belt, Pluto was seen in breathtaking detail when New Horizons passed within 12,500 kilometres (7,770 miles) of it.

7 August 2018
The hydrogen wall
9 En route to Arrokoth, New Horizons' forward-looking instruments confirmed the existence of the 'hydrogen wall', a layer of hot hydrogen gas just beyond the heliopause.

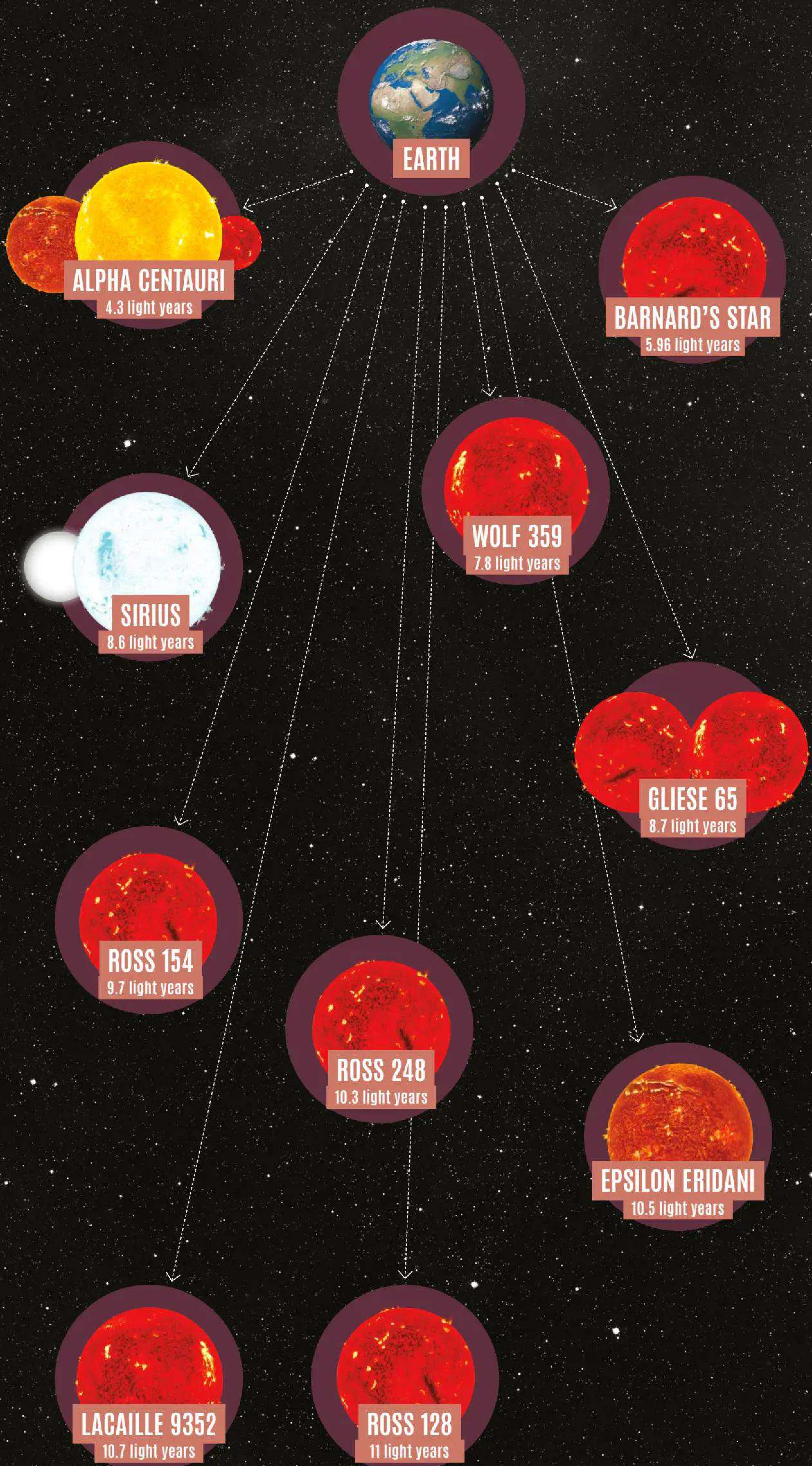
1 January 2019
Arrokoth arrival
10 New Horizons' next encounter after Pluto was with a much smaller Kuiper Belt object, known at the time as 2014 MU69, but since named Arrokoth.

COMMUNICATION BREAKDOWN

The last 12 months have been a stressful time for the operations of Voyager 1. In November 2023, the data that the interstellar explorer sent back to Earth became nonsensical – the binary code that Voyager 1 transmits back home was no longer readable. The distance between Earth and Voyager 1 made fixing this issue an arduous task, with a signal from operators taking 22.5 hours to reach the spacecraft and it then taking another 22.5 hours to receive a response from interstellar space. Yet despite these difficulties, in early March 2024, NASA engineers got a hint at what the issue with Voyager 1 was, and by April they were receiving data back from the spacecraft that once again made sense, and Voyager 1 was back in communication with Earth fully by mid-June.

INTERSTELLAR ROAD MAP

Given how difficult it is to travel far from Earth, where might our interstellar travels take us?



THE LOCATIONS

Alpha Centauri
Distance from Earth: 4.3 light years
Current travel time: 30,000 years
Interstellar speed travel time: 43 years
This three-star system includes Proxima Centauri, the nearest star to Earth after the Sun. It's confirmed there are at least two planets around this star.

Barnard's Star
Distance from Earth: 5.96 light years
Current travel time: 42,500 years
Interstellar speed travel time: 60 years
One of the fastest moving stars in the galaxy, this is also the closest star to Earth, after the Sun, that is visible from the Northern Hemisphere.

Wolf 359
Distance from Earth: 7.8 light years
Current travel time: 55,500 years
Interstellar speed travel time: 78 years
This red dwarf is located in the constellation of Leo and can only be seen through a large telescope.

Sirius
Distance from Earth: 8.6 light years
Current travel time: 61,250 years
Interstellar speed travel time: 86 years
Sirius is the brightest star in the night sky as it is one of the closest to us. It is part of a binary star system.

Gliese 65
Distance from Earth: 8.7 light years
Current travel time: 62,350 years
Interstellar speed travel time: 87 years
This star, seen in the constellation of Cetus, is actually a binary system of two stars encircling each other every 26.5 years or so.

Ross 154
Distance from Earth: 9.7 light years
Current travel time: 69,100 years
Interstellar speed travel time: 97 years
This star, found in the constellation of Sagittarius, can only be seen with apertures of three inches or larger.

Ross 248
Distance from Earth: 10.3 light years
Current travel time: 73,750 years
Interstellar speed travel time: 103 years
This small star in the constellation of Andromeda emits just 0.2 per cent of the Sun's light.

Epsilon Eridani
Distance from Earth: 10.5 light years
Current travel time: 75,000 years
Interstellar speed travel time: 105 years
This bright star, visible with the naked eye, has a confirmed planet orbiting around it and has been a popular interstellar travel target in science fiction.

Lacaille 9352
Distance from Earth: 10.7 light years
Current travel time: 76,700 years
Interstellar speed travel time: 107 years
Visible in the Southern Hemisphere with binoculars, this star is smaller and cooler than our Sun.

Ross 128
Distance from Earth: 11 light years
Current travel time: 78,000 years
Interstellar speed travel time: 110 years
Ross 128 is a red dwarf star whose orbit around the Milky Way will bring it closer to us in the future.

Borisov showed the usual activity that marked it out as a comet. It is also a more traditional spherical shape than 'Oumuamua. Like its strangely shaped interstellar compatriot, however, 2I/Borisov is moving too fast to become a permanent fixture in the Solar System and is expected to return to interstellar space. However, the Solar System is capable of capturing visitors from interstellar space on a more permanent basis.

Rogue planets are worlds that have been ejected from their home systems to wander interstellar space alone. New research has shown that the gravitational influence of the Sun could ensnare such a runaway planet and hold it at 241,000 AU away. That's equivalent to a distance of 3.81 light years, meaning these worlds would orbit the Sun almost as far away as the nearest star system, Alpha Centauri, which is 4.4 light years away. An interesting outcome of this is that it would be possible for these captured rogue planets to be exchanged between the Solar System and Alpha Centauri. That means planetary systems may overlap in interstellar space.

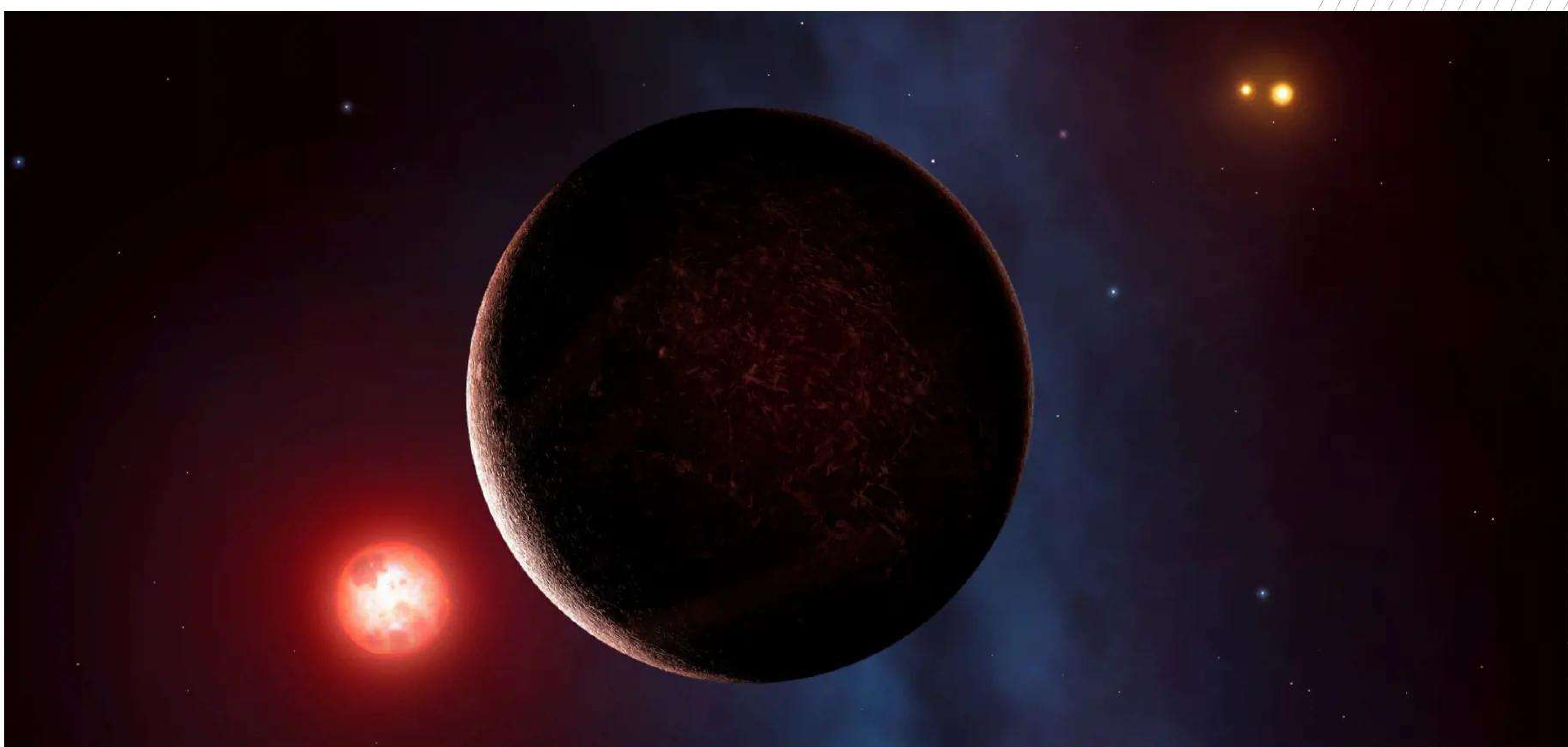
One of the requirements of a planet that can be grabbed by the Sun is that it would have to be travelling at speeds of around a few hundred miles an hour, thus much slower than the interstellar objects 2I/Borisov and 'Oumuamua. This slower speed means that these captured rogue planets remain a fixture of the Solar System, orbiting the Sun at vast distances through interstellar space for millions of years before gradually spiralling inwards towards the Sun and causing havoc with the other planets. The idea shows that the Sun's gravitational influence extends way beyond the impact of its solar wind.

This also means that there's a lot more to learn about interstellar space and that another in-situ interstellar spacecraft to join Voyager 1 and 2 would be of the utmost value. "As our only observers in interstellar space, we hope the two Voyagers can continue to make their measurements for several more years. Beyond that, a number of scientists have examined the possibility of launching an interstellar probe that might be able to reach 500 AU in a mission lasting some 50 years," Kurth concludes. "This spacecraft would be instrumented with modern equipment specifically designed to study the interstellar medium." Maybe within the next century, humanity can finally cross the final frontier, at least in theory.

COULD ASTRONAUTS REACH INTERSTELLAR SPACE?

Sending robotic missions like Voyager 1 and 2 to interstellar space is brilliant, but how incredible would it be if a human could venture beyond the limits of the Solar System? Currently, the idea of an astronaut journeying beyond the Solar System and leaving the confines of our star is firmly rooted in science fiction. The distance is just far too great. The main human-carrying spacecraft for the Artemis Moon missions is the Orion capsule, which will travel between the Moon and Earth at around 39,590 kilometres (24,600 miles) per hour. Let's say it can hold this speed constantly as it travels the most direct route to the heliopause. That is estimated to be around 17 billion kilometres (10.5 billion miles) away, which makes this a journey that would take Orion around 51 years. Any astronauts hoping to voyage beyond the limits of the Solar System better pack a comfy neck pillow and plenty of in-flight movies.

Robert Lea
Space science writer
Rob is a science writer with a degree in physics and astronomy. He specialises in physics, astronomy, astrophysics and quantum physics.



The Alpha Centauri star system is known to host at least two exoplanets

FOCUS ON

STELLAR VAMPIRES MAY FEED ON HIDDEN STARS IN THEIR SYSTEMS

Some massive stars may exist in systems of not just two, but three interacting stellar bodies

Reported by Robert Lea

Some star systems believed to host two stellar bodies may actually have a hidden third – a traitorous star that could help push one of its sparkling companions towards the other as the latter feasts on its victim like a vampire. Such is a discovery made by University of Leeds scientists analysing data from the European Space Agency's (ESA) Gaia mission, which pinpoints the positions of a billion stars throughout the Milky Way. The revelation could transform our understanding of how the most massive stars in the cosmos evolve.

These so-called vampire stars, more officially known as 'Be' stars, are characteristically surrounded by rings of superheated gas. They're a subcategory of B stars, which are extremely bright and between 2 and 16 times more massive than the Sun. Yet despite the fact that Be stars were discovered around a century and a half ago, in 1866, quite how the discs around these massive stars form has remained a puzzle.

The leading theory thus far suggests Be discs are created as the stars rapidly rotate, causing them to rip stellar material away from their companion stars. This material stripped from the victim star is also believed to carry along angular momentum that further 'spins up' the rotation of the feeding stellar vampires. The team's new research further bolsters the theory, suggesting Be stars might live in triple star systems rather than double star systems, interacting with two companion stars, rather than just one.

"We observed the way the stars move across the night sky over longer periods like ten years, and shorter periods of around six months," Leeds University PhD student Jonathan Dodd said. "If a star moves in a straight line, we know there's just one star, but if there is more than one we will see a slight wobble, or in the best case, a spiral." The team applied this principle across two groups of stars: B stars in general and Be stars in particular. The researchers then

An illustration of a massive vampire star surrounded by a ring of material and orbited by a stripped stellar victim

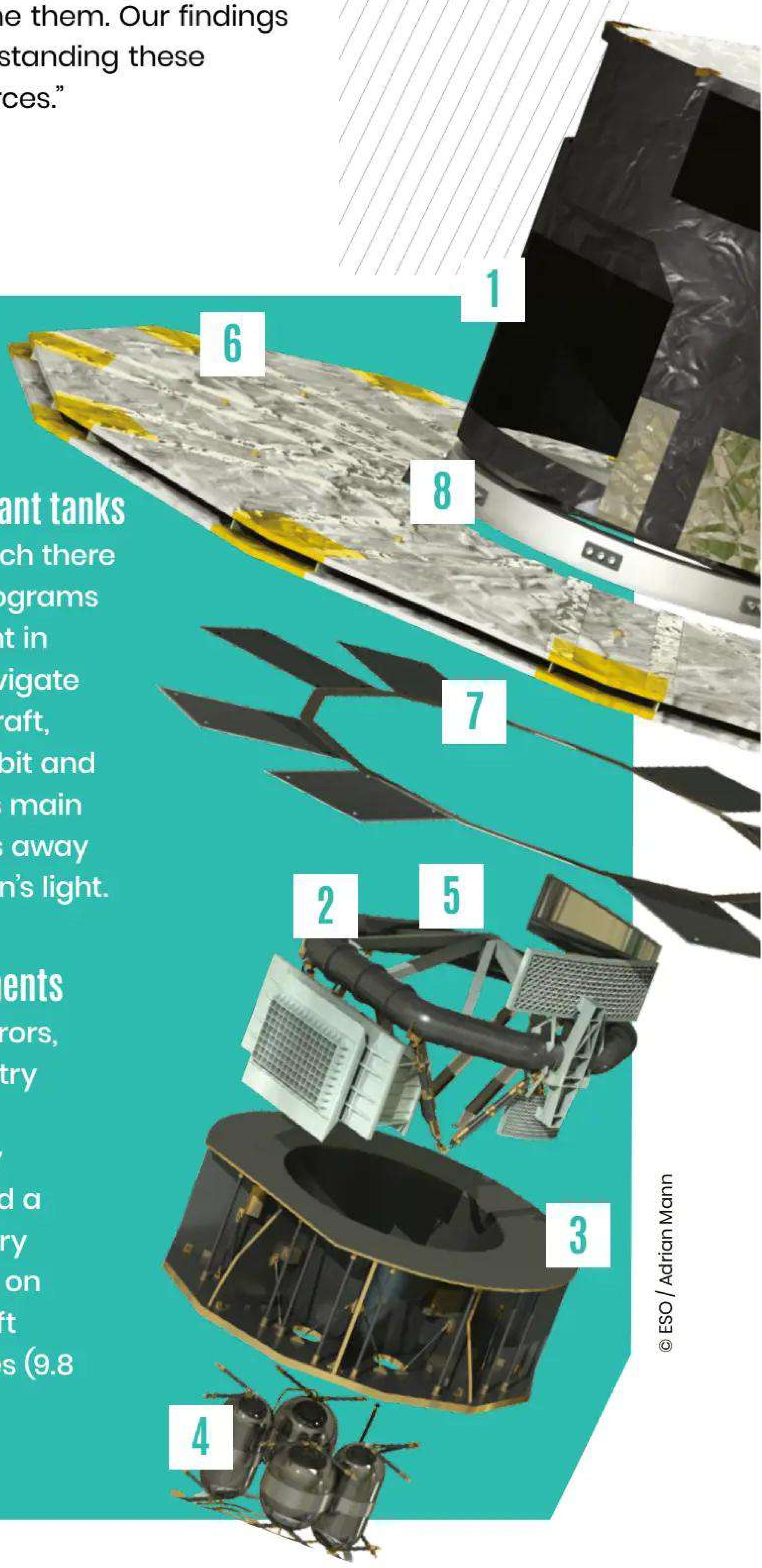
found the Be stars seemed to have a lower rate of companions than the B stars did. This was somewhat confusing. "We'd expect them to have a higher rate," Dodd said.

Team leader René Oudmaijer, a professor at Leeds University, believes the lack of companion star detection might stem from the fact some stars grow too faint to be seen after getting feasted upon by Be stars. The team also found distances between companion stars in B star systems versus Be star systems appear to be similar. That's strange as well, because Be stars are supposed to be wrapped in a stellar cloak of stripped-off material, while B stars aren't. These two components together imply there could be a hidden third star in Be systems pushing feasted-upon stars closer to the Be stars, acting almost like cosmic thralls and supplying their vampire star masters with victims to dine on. Once the victim companion stars get close enough to the Be stars, the former's mass can be transferred. Rather than falling to the vampire star directly, however, the team says this material first forms a swirling disc around the victim star. Perhaps Be star companions become victims, in line with the Be stellar disc theory, ultimately growing too small and faint to be seen after being sucked dry.

The team's findings could have implications outside of stellar physics, too, possibly teaching scientists more about how stars die to become black holes or neutron stars. They could also shed light on how binaries of those stellar remnants themselves generate ripples in the very fabric of space-time, called gravitational waves. "There's a revolution going on in physics at the moment around gravitational waves. We have only been observing these gravitational waves for a few years now, and these have been found to be due to merging black holes," Oudmaijer explained. "We know that these enigmatic objects exist, but we don't know much about the stars that would become them. Our findings provide a clue to understanding these gravitational-wave sources."

"If a star moves in a straight line, we know there's just one star, but if there is more than one we will see a slight wobble, or in the best case, a spiral"
Jonathan Dodd

GAIA'S ANATOMY



© ESO / Adrian Mann

1 Thermal tent This thermal tent covers the payload module and protects it from being exposed to extraneous radiative thermal inputs.

2 Payload module This module accommodates the two telescopes and electronics in order to manage and process the raw data collected.

3 Service module This contains equipment to maintain basic control, provide power, store data and process video data.

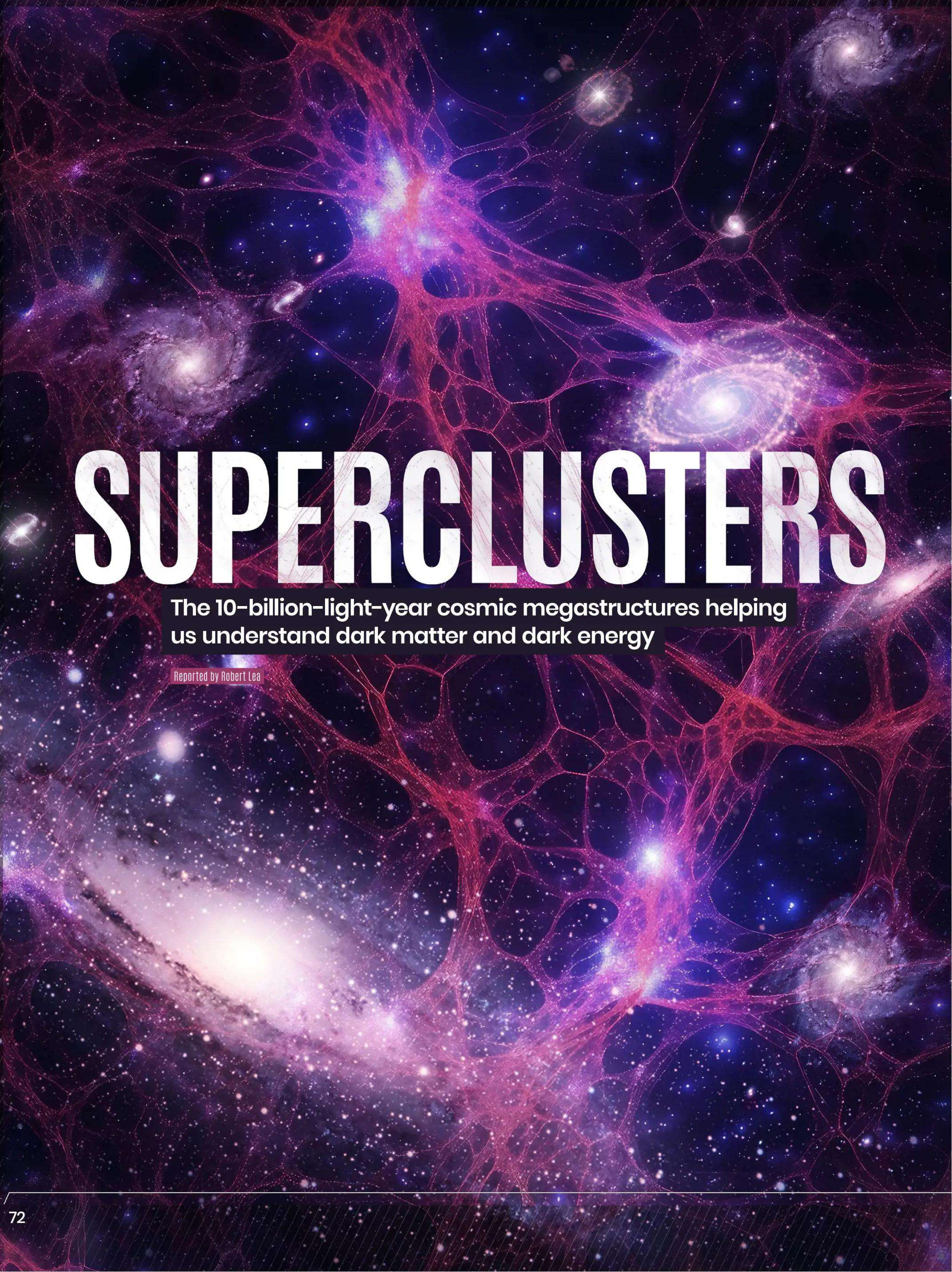
4 Propellant tanks At launch there was 400 kilograms of propellant in order to navigate the spacecraft, keep it in orbit and orientate its main instruments away from the Sun's light.

5 Sensitive sensors Gaia has sensors that are so powerful they can detect faint objects with a luminosity 400,000 times lower than the naked eye is capable of seeing.

6 Deployable sunshield Stretching out roughly 10.2 metres (33.5 feet), the sunshield protects Gaia's sensitive instruments and helps keep them cool enough to operate properly.

7 Solar panels There are eight solar panels attached to the outside of the deployable sunshield. These collect the Sun's light and harness it for energy to power the spacecraft.

8 Instruments Ten mirrors, an astrometry function, a photometry function and a spectrometry function, all on a spacecraft three metres (9.8 feet) tall.



SUPERCLUSTERS

The 10-billion-light-year cosmic megastructures helping us understand dark matter and dark energy

Reported by Robert Lea

How truly insignificant our own planetary system is on the grand scale of the universe. Like cosmic nesting dolls, the Solar System is part of the Milky Way, with the Sun just one of around 100 billion stars, and the Milky Way is just one of over 54 members that comprise the Local Group of galaxies. And this Local Group is part of something even larger – the Virgo Supercluster. This supercluster contains the Milky Way, Andromeda and at least 100 groups and clusters of galaxies spanning a width of around 110 million light years. The mass of the Virgo Supercluster, or the Local Supercluster, is estimated to be equivalent to around 1.5 quadrillion suns – that's 15 followed by 14 zeros. That means our Solar System, estimated to be three light years across, could fit within the width of our home supercluster around 37 million times.

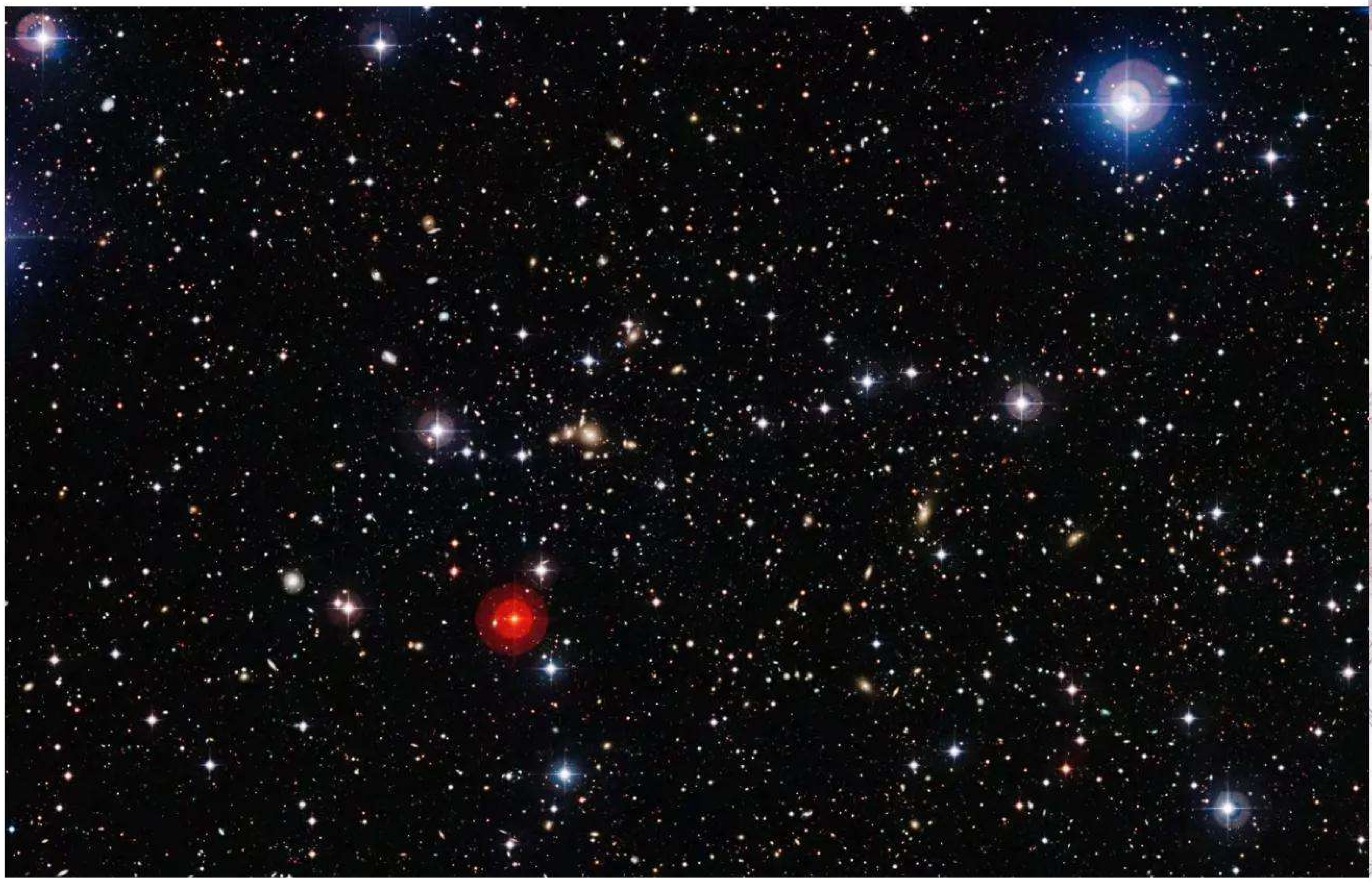
And the Virgo Supercluster is also part of something bigger… In 2014, astronomers discovered that the Virgo Supercluster is an 'appendage' of the larger Laniakea Supercluster, with Laniakea being Hawaiian for 'open skies' or 'immense heaven'. This is an apt name for a supercluster that contains 100,000 to 150,000 galaxies and stretches for an estimated 520 million light years, with a mass equivalent to around 100 quadrillion Suns. But perhaps even more shocking is the fact the Laniakea Supercluster is just one of an estimated 10 million superclusters in the observable universe.

"Superclusters represent the largest and most massive aggregations of matter in the universe," Shishir Sankhyayan, a postdoctoral fellow at the University of Tartu, tells **All About Space**. "To draw a rough analogy, they are akin to vast mountain ranges amid the otherwise relatively flat expanses of Earth. Unlike smaller structures such as galaxies or our Solar System, superclusters are not necessarily gravitationally bound structures." As that hints, it's not easy answering the question of what a supercluster actually is.

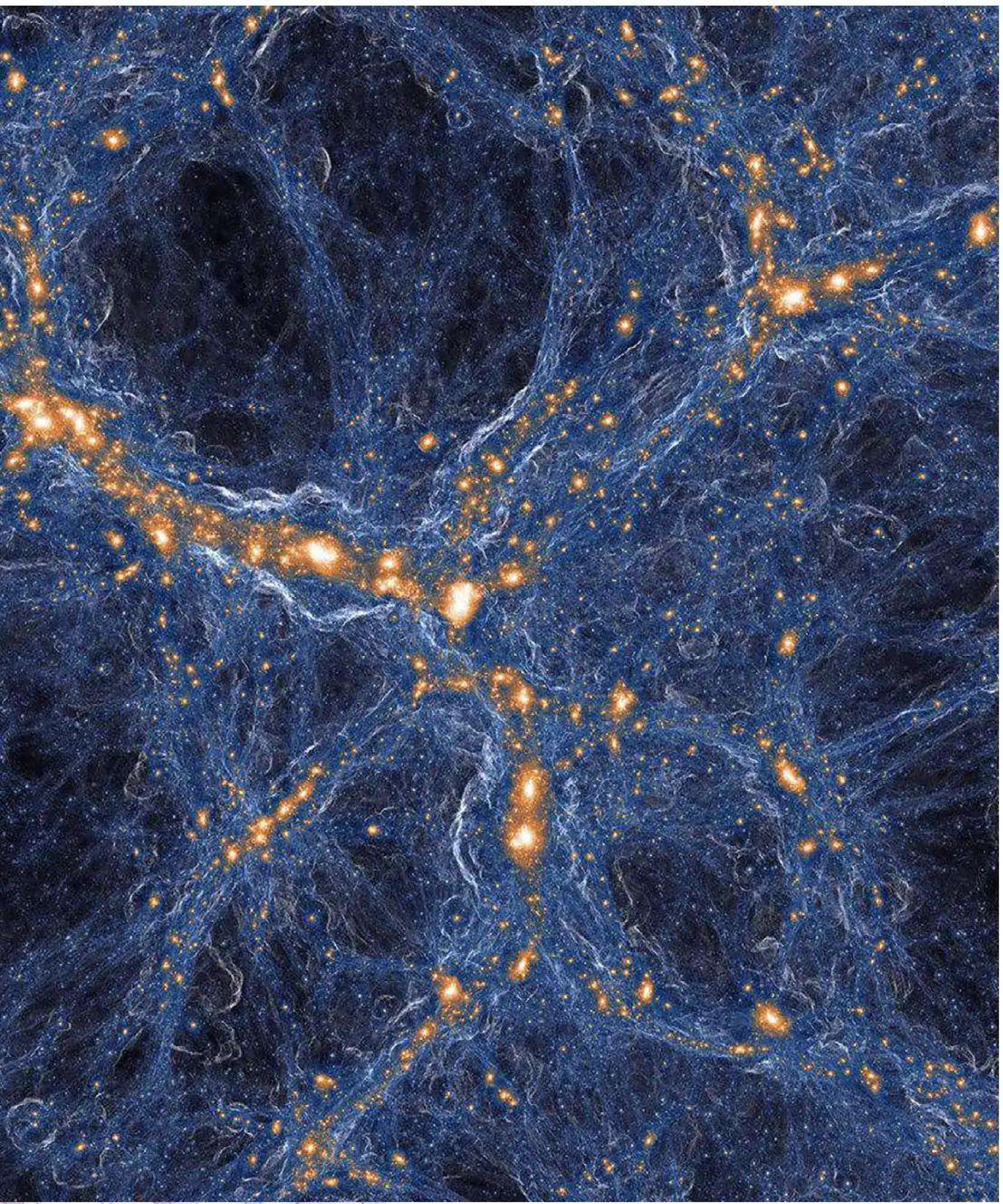
As Sankhyayan explains, the term 'supercluster' is still a topic of active debate in astronomical circles. Some scientists consider superclusters to be gravitationally bound entities, while other researchers define them based on density. Others focus on the large-scale convergence of galaxies moving at similar speeds. He adds that this is complicated further when the choice of astronomical objects, such as individual galaxies, galaxy clusters or other things, is factored in and used to define supercluster types.

In broad terms, a supercluster is generally considered to be a gathering of three to ten galaxy clusters that spans up to 200 million light years. The major ramification of the existence of these tremendous cosmic structures is the revelation that galaxies are not evenly distributed through the universe. The cosmos seems to be populated by superclusters and relatively empty voids as opposed to the view that the universe is even, or 'homogeneous', in all directions.

"Superclusters represent the largest and most massive aggregations of matter in the universe"
Shishir Sankhyayan



A deep-field image of Abell 901/902, located just over 2 billion light years from Earth



▲ A simulation shows galaxies growing on a vine of dark matter

▼ A map of our home supercluster, called Laniakea

The first hints of the uneven or 'non-homogenous' and 'non-isotropic' distribution of galaxies was provided in 1932 by the American astronomers Harlow Shapley and Adelaide Ames. This came from their observation that the number of brighter galaxies differed between the north and south planes of the Milky Way. What they had actually seen was a fraction of the Virgo Supercluster. Following this, the man who discovered Pluto, Clyde Tombaugh, showed Edwin Hubble – who first discovered that galaxies beyond the Milky Way existed in 1928 – a map of a supercluster, but Hubble rejected the concept.

Gérard de Vaucouleurs suggested in the early 1950s that our galaxy and its Local Group cluster were part of a much larger gathering, but the idea was met with mostly silence from the scientific community.

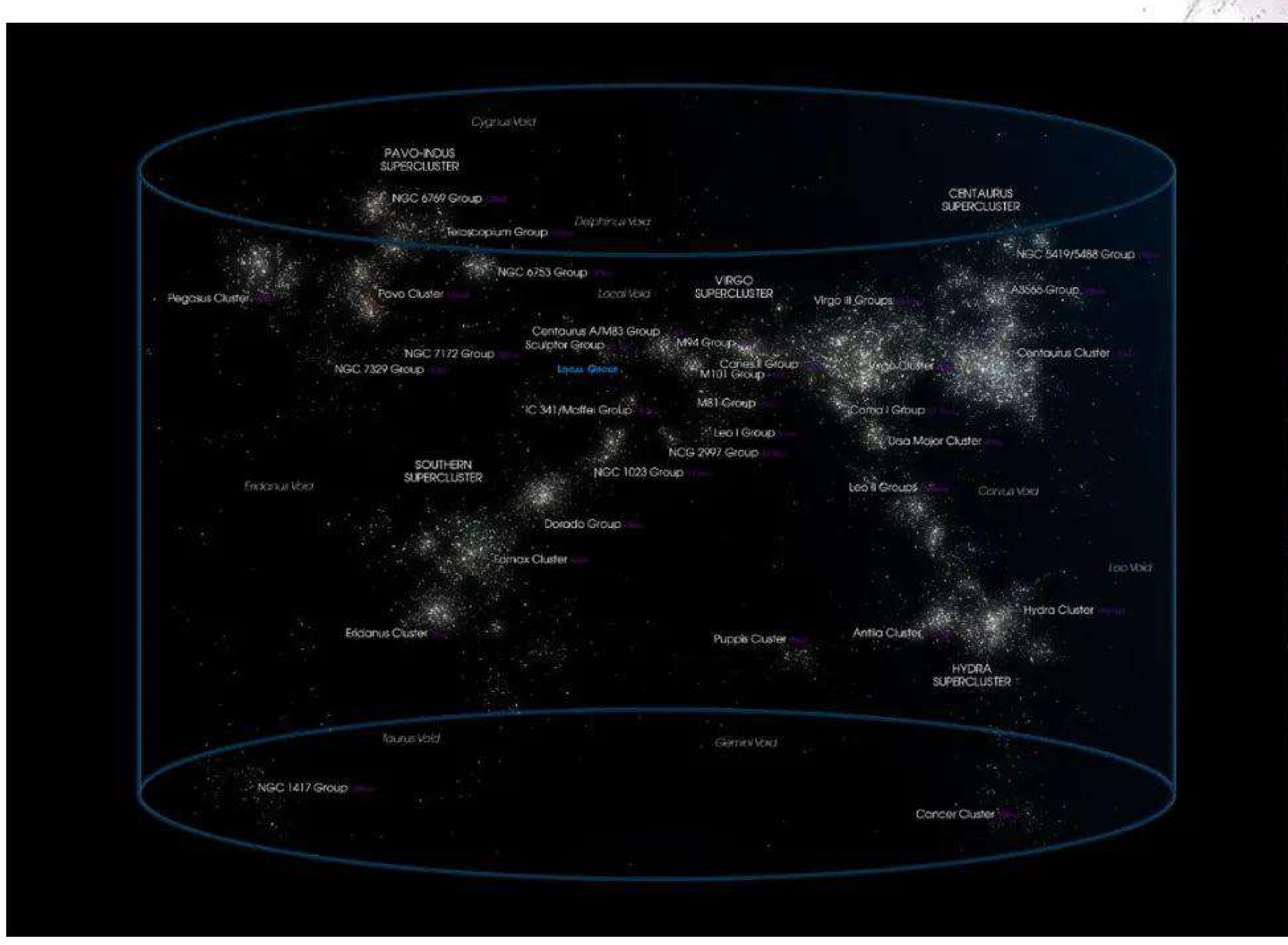
> **"Superclusters may have been present when the universe was less than 1 billion years old"**
> **Shishir Sankhyayan**

Undaunted, de Vaucouleurs and fellow astronomers Erik Holmberg and George Abell featured the concept of superclusters in the 1958 Abell catalogue of galaxy clusters. The influential astronomer Abell described superclusters as "second-order clusters," referring to the fact that they are clusters of clusters.

Superclusters moved from theory to reality in the 1970s when improved techniques and technology in astronomy allowed astronomers to begin developing a 3D picture of galaxies and the distances between them. This led to the discovery of the Coma Supercluster, a 20-light-year-wide gathering of over 3,000 galaxies located 300 million light years away, by Stephen Gregory, Laird Thompson and William Tifft. By the 1980s, the existence of superclusters was widely accepted by the astronomical community.

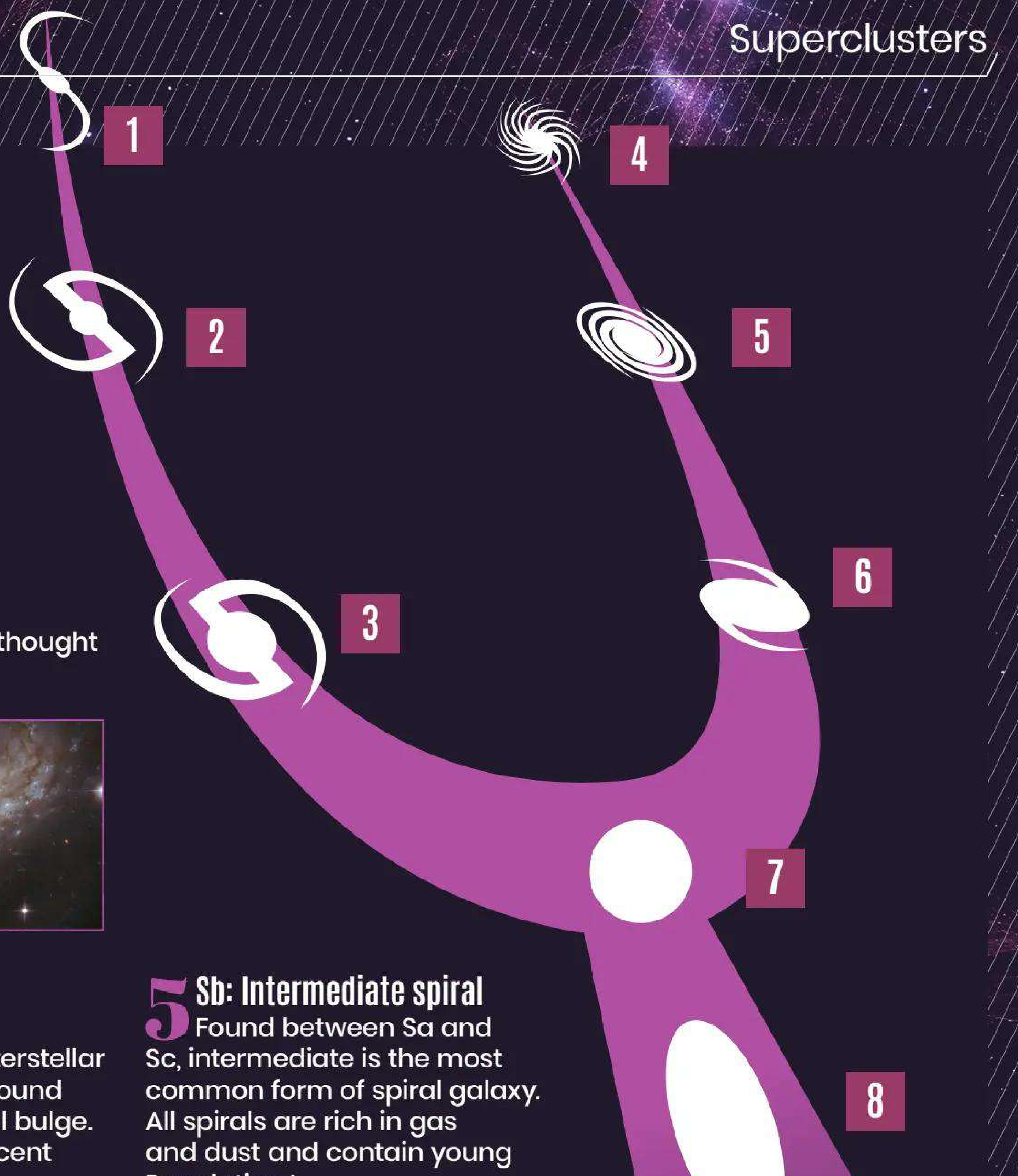
Astronomers now think that superclusters fill around ten per cent of the universe's volume, but while most galaxies and galaxy clusters are thought to be part of a high-density region or supercluster, there are still examples of seemingly independent galaxies. Sankhyayan explains that there are hints at differences between galaxies that are part of superclusters and those that are not. "Superclusters encompass diverse density environments. Galaxies within them are influenced more by local conditions than by broader surroundings," he says. "However, studies show that on average, galaxies within superclusters tend to be redder and exhibit lower rates of star formation compared to those within a global low-density environment. Additionally, galaxy clusters within superclusters are typically more massive than clusters found elsewhere."

Yet despite four decades of research, particularly by Estonian astronomer Jaan Einasto, who has been influential in understanding the large-scale structure of the universe, these vast cosmic structures are still somewhat shrouded in mystery. "The origins of galaxy superclusters remains a topic of ongoing research. Scientists are exploring whether they formed relatively recently in the universe's history or if they have existed since its earliest stages," Sankhyayan says. "The studies led by Einasto and his team using cosmological simulations indicate that superclusters may have been present when the universe was less than 1 billion years



Source: Wikipedia Commons © Andrew Z. Colvin; TNG Collaboration

HUBBLE'S TUNING-FORK CLASSIFICATION OF GALAXIES



1 SBc: Open barred spiral

This type of galaxy has the least defined central bar and a looser structure.

2 SBb: Intermediate barred spiral

Our Milky Way Galaxy is thought to be of this type.

3 SBa: Barred spiral

The B states that the galaxy has a bar of stars at its centre that the spiral arms wind away from. Just like the normal spiral galaxy classification system, the lower-case letter refers to how tightly wound the spiral arms are.

4 Sc: Open spiral

With more young Population I stars and interstellar gas, they have loosely wound arms and a small central bulge. These consist of ten per cent gas and dust, compared with two per cent in Sa spirals.

5 Sb: Intermediate spiral

Found between Sa and Sc, intermediate is the most common form of spiral galaxy. All spirals are rich in gas and dust and contain young Population I stars, along with older Population II stars.

6 Sa: Spiral

The spiral arms are tightly wound, with a bright central bulge and small amounts of interstellar gas. The S refers to this being a spiral galaxy and the lower-case letter refers to how tightly wound the galaxy arms are.

7 S0: Lenticular

These have a prominent central bulge, but no spiral arms. An intermediate type between E7 and Sa, they are like elliptical galaxies because they tend to contain old stars and have less gas and dust than spirals.

8 E5 and E7: Elongated ellipticals

The most flattened galaxies are given this designation. Elliptical galaxies tend to contain old stars and are loosely structured, indicating they were formed before spiral galaxies.

9 E0: Spherical

The roundest looking galaxies are given this rating. This corresponds to the physical structure of the galaxy. The rest of the E-type galaxies refer to how they look from Earth rather than their actual structure.

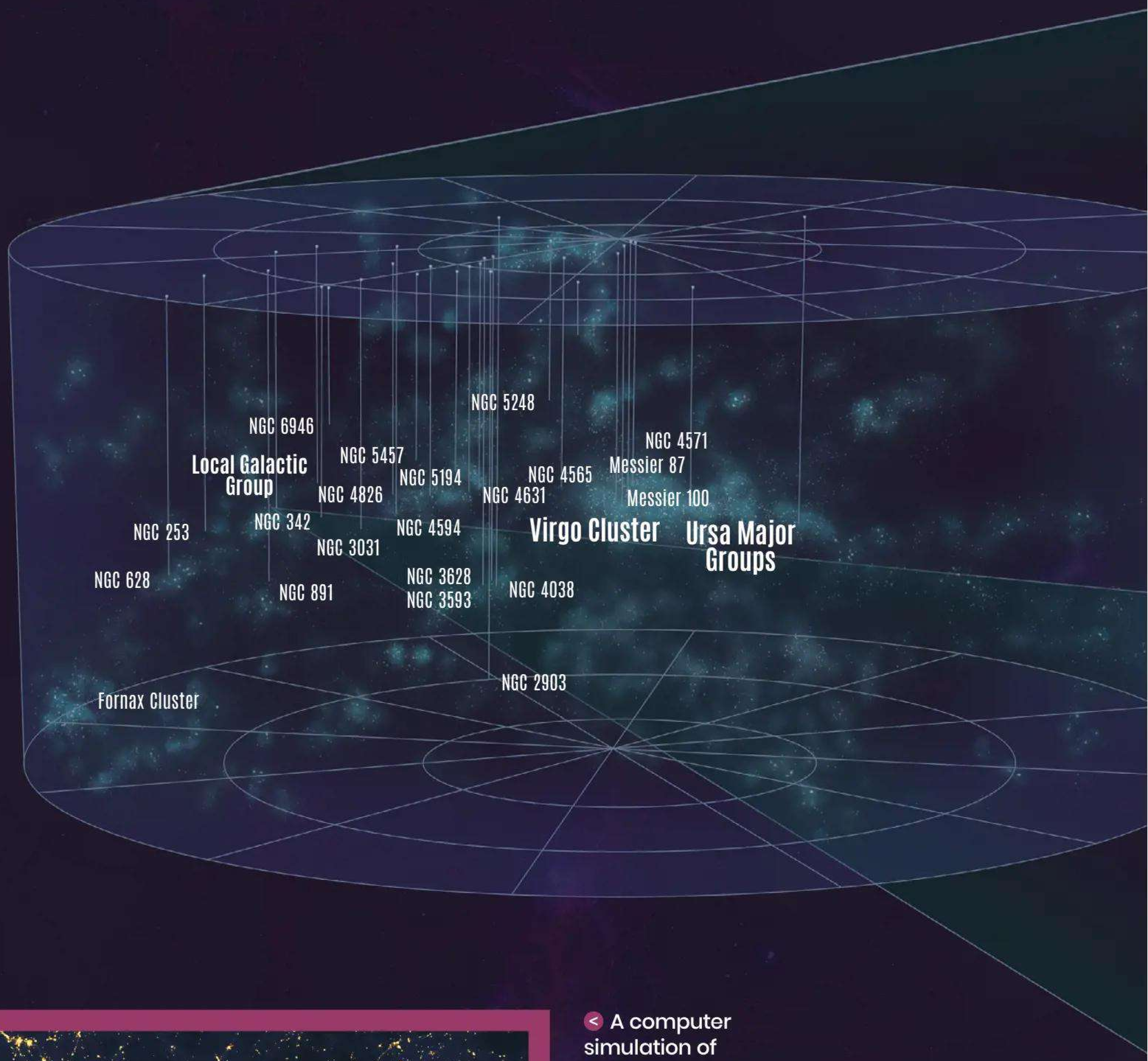
10 E3: Elliptical

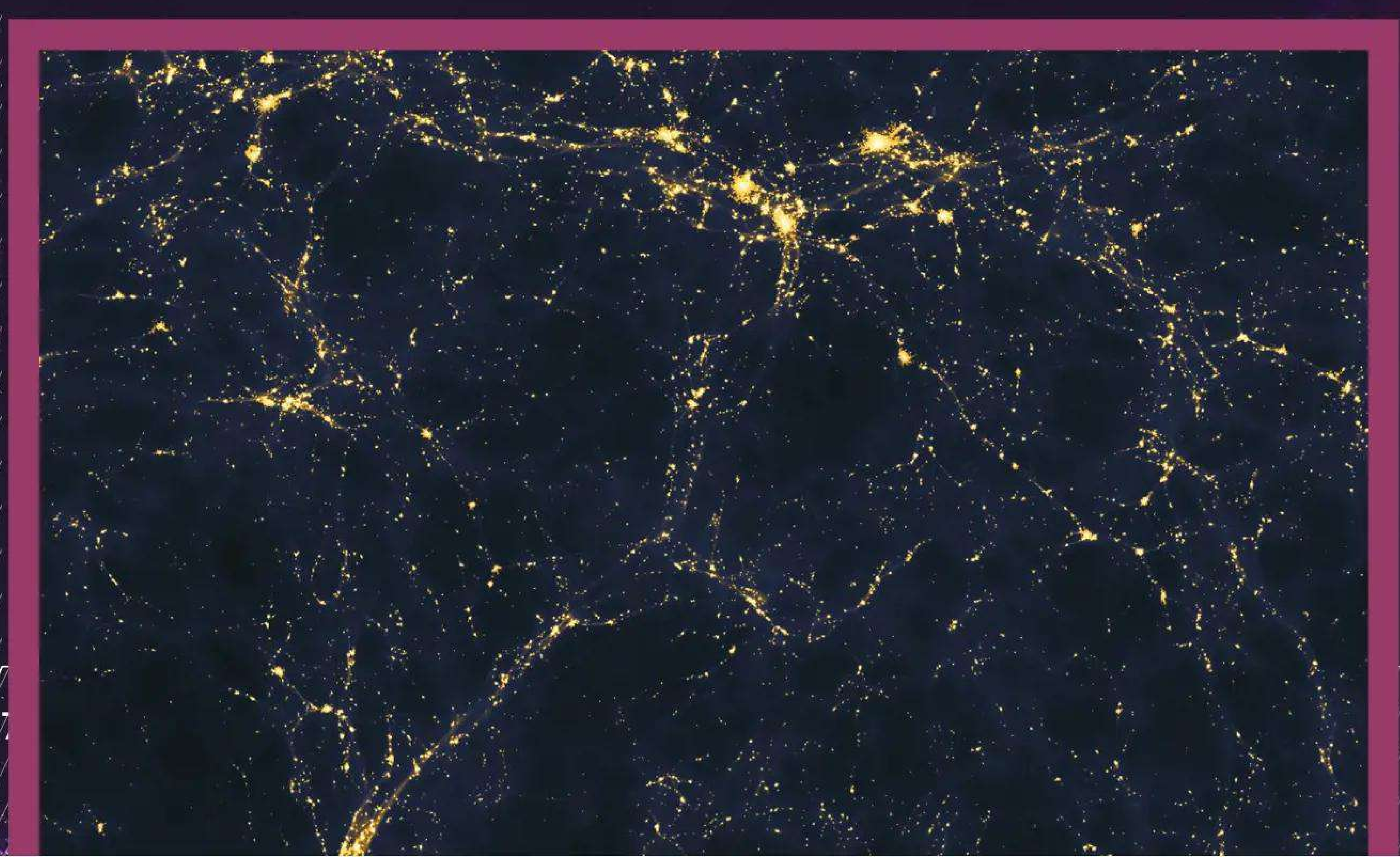
Elliptical galaxies are given higher numerical designations according to how flat they look. The E prefix refers to this being an elliptical galaxy and the number refers to how flat the galaxy is.

THE LARGEST THING IN THE UNIVERSE?

THE HERCULES-CORONA BOREALIS GREAT WALL

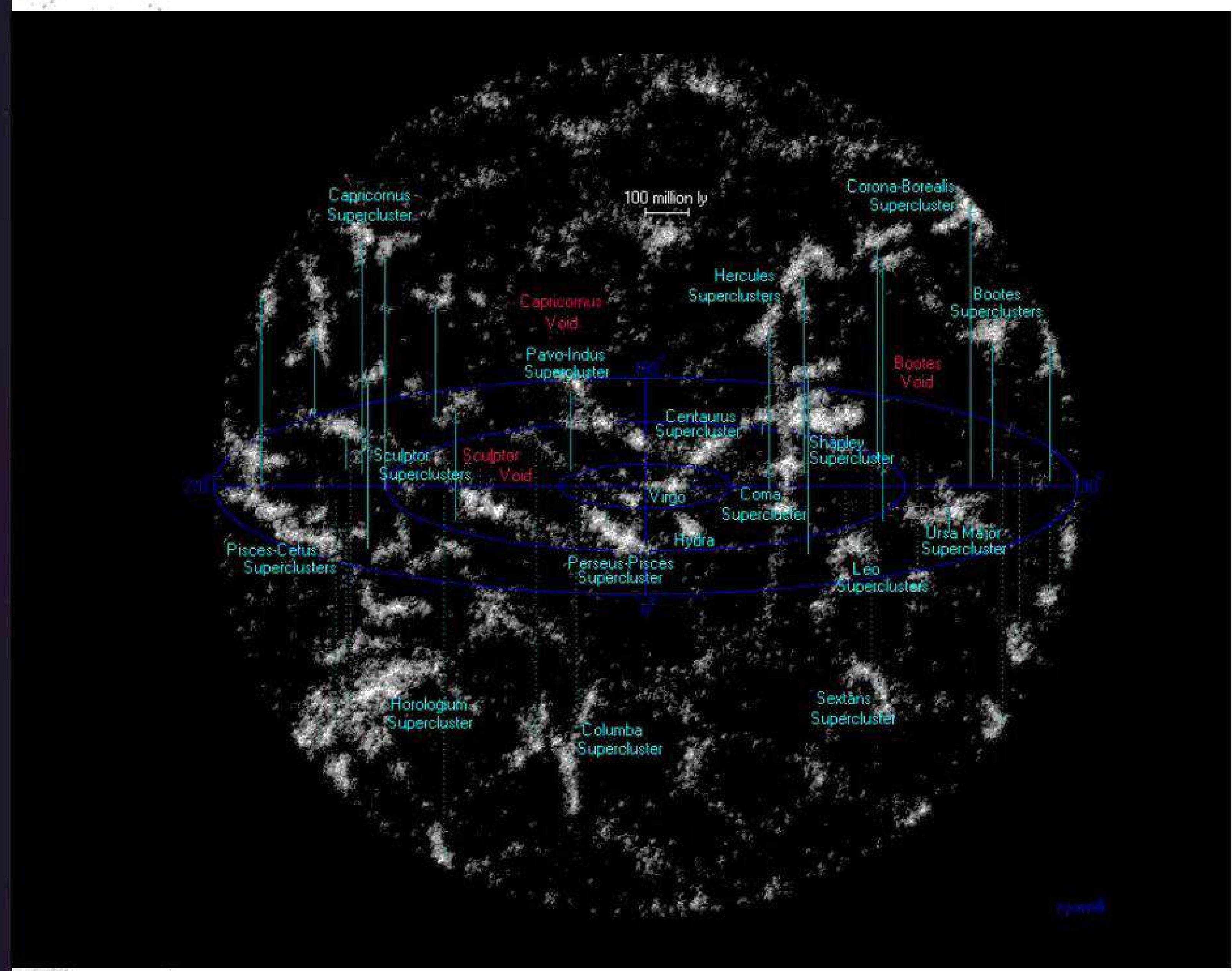
It likely comes as a surprise that the largest single structure in the entire universe that we know of isn't actually a supercluster. This distinction goes to the Hercules-Corona Borealis Great Wall, which is believed to be one of the filaments hanging from the cosmic web and is integral to the formation of superclusters. The Hercules-Corona Borealis Great Wall has an estimated length of 10 billion light years and a width of 7 billion light years. To put that into perspective, the entire universe is only thought to be 93 billion light years wide. Also, the universe is 13.8 billion years old, and it would take 10 billion years for light to travel the length of the Hercules-Corona Borealis Great Wall. Discovered through the clustering of gamma-ray bursts, the existence of the Hercules-Corona Borealis Great Wall is still a contentious matter debated by scientists.





< A computer simulation of the cosmic web, which provides the scaffold on which superclusters grow

↑ A map of superclusters and supervoids within around 1 billion light years of Earth



old. However, confirming this through observations is still a significant challenge that lies ahead."

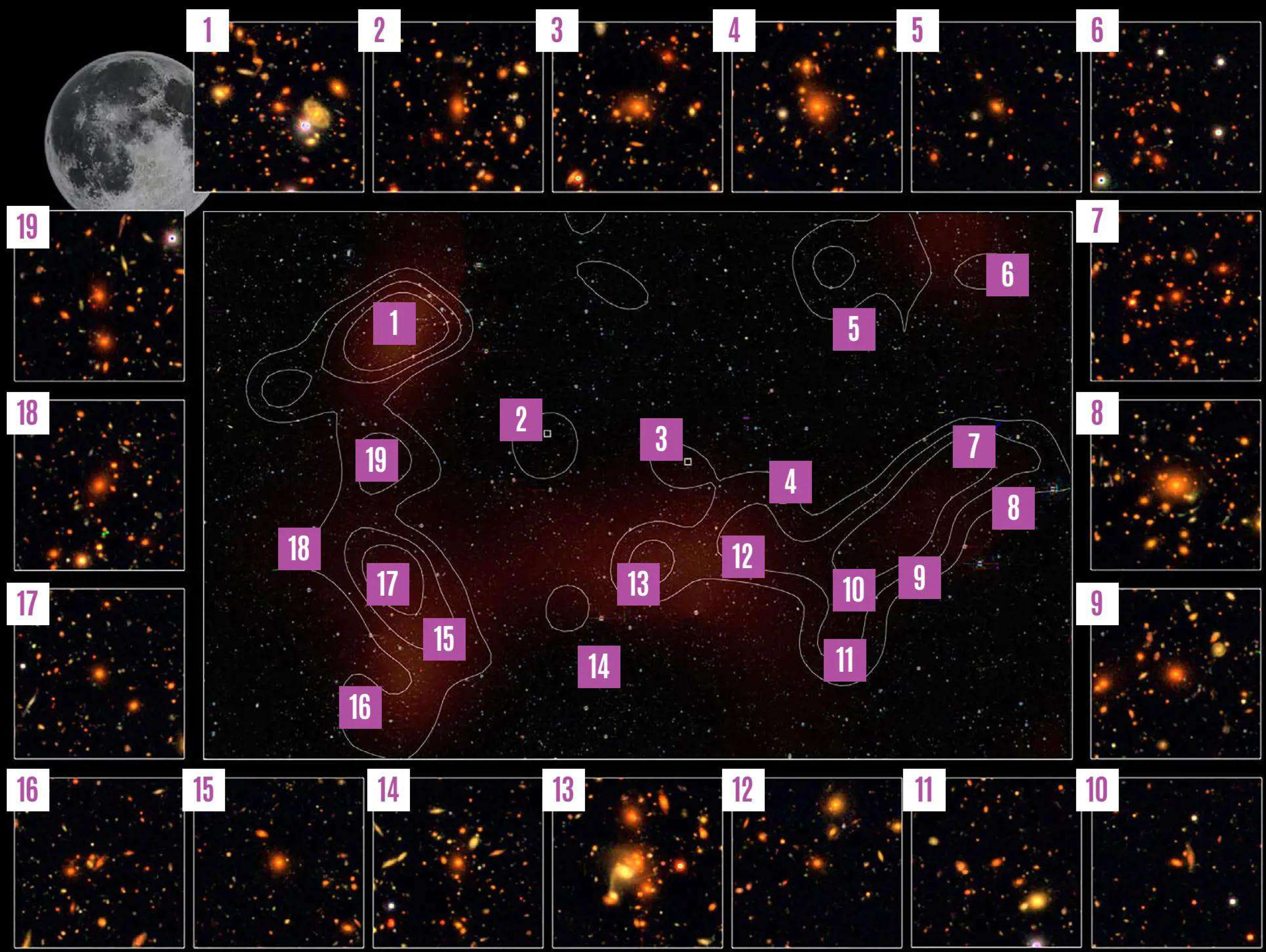
Currently, the earliest and thus most distant supercluster that astronomers are aware of is the supercluster SPT2349-56, located 12 billion light years away and therefore seen as it was when the 13.8-billion-year-old universe was just 1.8 billion years old. Part of the reason superclusters are somewhat shrouded in mystery is that their origins and their evolution seem to be wrapped up in the universe's two most mysterious entities: dark matter and dark energy. This means studying superclusters is of the utmost importance to astronomers and cosmologists, as this investigation can help them answer questions about two of the biggest mysteries in science, sometimes collectively described as the dark universe.

Dark energy is the force driving the acceleration of the expansion of the universe. Dark matter, on the other hand, is a mysterious substance that neither interacts with matter nor with light. The only reason scientists suspect it exists is because of its interactions with gravity, which then has an influence on 'everyday' visible matter and light.

These dark universe entities are considered such pressing concerns because together they account for 95 per cent of the universe's matter and energy budget. That means the 'stuff' we understand, which is made up of atoms – stars, planets, interstellar gas, asteroids and our own bodies – makes up just five per cent of the cosmos' contents, and we are figuratively in the dark about the rest.

"The structure of matter in the universe, including galaxies and dark matter, forms a web-like structure known as the cosmic

© Source: Wikipoida Commons; Andrew Pontzen/Fabio Governato/Hiranya Peiris; Richard Powell



web," Sankhyayan says. "This structure consists of various components, such as clusters of galaxies, galaxy walls, dark matter filaments and vast voids largely devoid of matter. Superclusters, being the largest entities, can be imagined as large structures sitting on top of this cosmic web formation." To picture the cosmic web, imagine clumps of dark matter, within which sit galaxies, with these 'nodes' linked together by fine filaments that are also composed of dark matter, gas and dust. Investigating superclusters and how they warp the passage of light can reveal distortions that hint at where these dark matter filaments are.

While dark matter, through its gravitational influence, draws superclusters together, dark energy expands the very fabric of space. Acting almost as a force of 'antigravity', it could be destroying superclusters. Theoretical astrophysicist and science communicator Ethan Siegel argues in a 2022 Big Think article that as dark energy pushes galaxies apart in superclusters, the apparent relationships between galaxies in superclusters are dissolving these structures.

Sankhyayan explains how this means that the shape and distribution of matter in the universe – in particular the structure of superclusters – are influenced by the amount of dark matter and dark energy present in the cosmos and the nature of these dark universe entities. Theoretical models of cosmology consisting of different values for dark energy and dark matter provide predictions about how the universe and these structures evolve. Observations of these superclusters could therefore help scientists better determine which of these models is the right one. "By studying superclusters, which are among the largest structures in the universe, scientists can refine and test theoretical models of cosmology that provide predictions about how the universe evolves and the properties of its structures," Sankhyayan says. "For instance, researchers can examine the distribution of superclusters within specific regions of the universe to constrain the accuracy of these models."

Searching for the distribution of superclusters has certainly led to some remarkable discoveries. Just this year, Sankhyayan and his colleagues' quest to understand the largest structures in

A COSMIC KAIJU

Before the discovery of the Einasto Supercluster, the most massive known supercluster also had one of the best names of any celestial body. The King Ghidorah Supercluster is named after the three-headed golden dragon antagonist from the *Godzilla* franchise and is located around 6.7 billion light years from Earth. It contains a whopping mass equal to 10 quadrillion Suns, and though it lost its mass crown to the Einasto Supercluster, at 1.3 billion light years, the King Ghidorah Supercluster remains the largest of these celestial structures.

> **"Superclusters can be imagined as large structures sitting on top of this cosmic web"**
> **Shishir Sankhyayan**

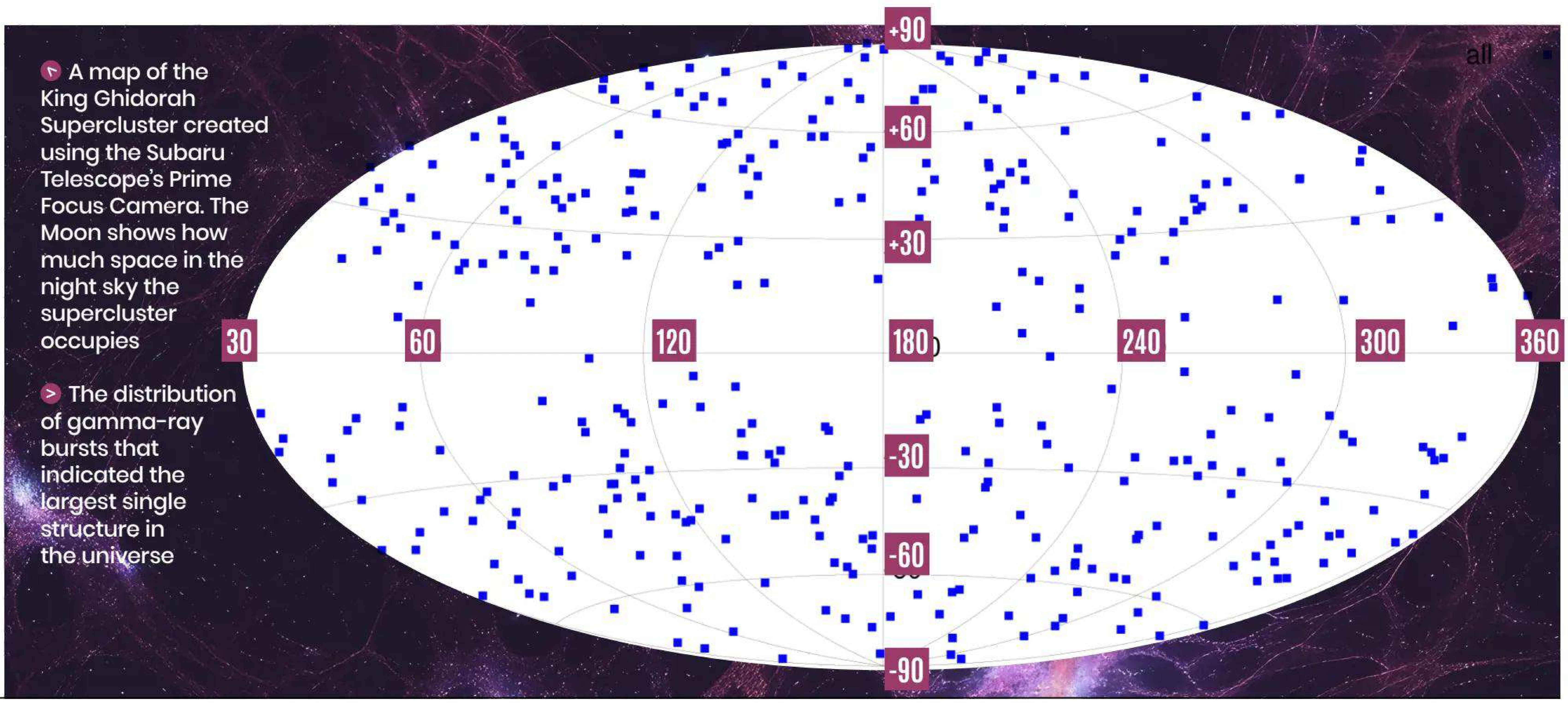
the cosmos led him and a team from Tartu Observatory to 662 new examples of superclusters. The typical mass of the superclusters discovered in this collection was around 6 quadrillion times that of the Sun, while the average width of these superclusters was 200 million light years across – around 2,000 times larger than the Milky Way. The most striking of these superclusters is a real outlier to these averages, however.

Located 3 billion light years away, the Einasto Supercluster – which was named in honour of Jaan Einasto and his pioneering work on the large-scale structure of the universe – is the most massive supercluster yet to be discovered. Sankhyayan explains that the Einasto Supercluster has a staggering mass equivalent to 26 quadrillion Suns, making it roughly 26,000 times more massive than our Milky Way. "While it is among the largest superclusters in the universe overall, it also stands out as the most massive supercluster within a range of distances from Earth spanning 700 million to 5 billion light years observed to date," Sankhyayan says. "Observing it provides a glimpse into its state as it existed 3 billion years ago."

The Einasto Supercluster is also remarkable for its sheer size, as well as the record-breaking mass of its contents. The newly discovered supercluster king is so vast that light emitted from one side of it would take 360 million years to travel to the opposite edge. For comparison, light would take around 106,000 years to travel across the diameter of the Milky Way. The discovery of the Einasto Supercluster and this collection of superclusters has delivered several surprises to Sankhyayan and the Tartu Observatory team and has demonstrated that there are plenty of surprising superclusters out there to be discovered and investigated.

"I found it quite surprising to observe a correlation between the size of this supercluster and its overdensity," Sankhyayan says. "However, this potential relationship demands confirmation through additional studies." This includes hints that dark energy may not be as effective at pushing galaxies in clusters apart as it is at pushing apart independent galaxies. Thus predictions of 'dissolving superclusters' – at least those that are gravitationally bound – could be premature. "While it was not unexpected to learn that in superclusters the expansion of the universe is proceeding at a slower rate compared to the overall expansion of the universe, discovering this through my own research was still enlightening," Sankhyayan concludes.

Robert Lea
Space science writer
Rob is a science writer with a degree in physics and astronomy. He specialises in physics, astronomy, astrophysics and quantum physics.



A map of the King Ghidorah Supercluster created using the Subaru Telescope's Prime Focus Camera. The Moon shows how much space in the night sky the supercluster occupies

The distribution of gamma-ray bursts that indicated the largest single structure in the universe

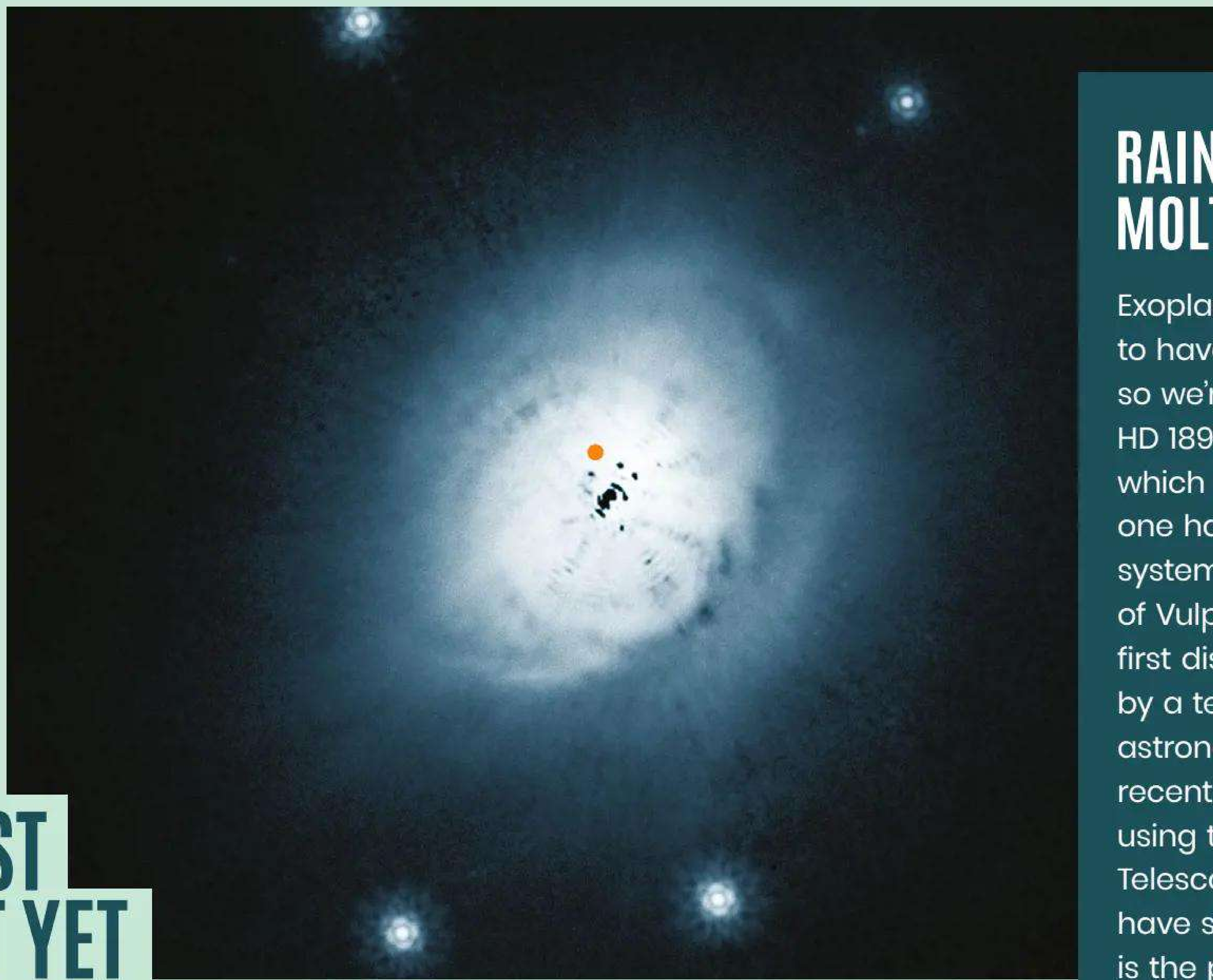
STRANGE NEW WORLDS

THE EXOTIC EXOPLANETS THAT DEFY THE LAWS OF PHYSICS

We're discovering and uncovering details about new exoplanets all the time, with some really weird worlds existing beyond the Solar System

Written by Ian Evenden

Ever since humans started discovering exoplanets – planets that orbit around stars other than the Sun – in 1992, scientists have been hunting for one similar to Earth. Exoplanets exist everywhere, around many different types of stars. Yet none of them are Earth-like. They're too big, too hot or too bathed in radiation from their star to support life as we know it. The search goes on, and as new data comes in from planet-hunting missions such as the Transiting Exoplanet Survey Satellite (TESS) and ground-based telescopes such as the Very Large Telescope (VLT), there's one thing that we can be sure about: many of the exoplanets we find will be extreme.



THE BIGGEST EXOPLANET YET

Discovering the precise size of an exoplanet is a tricky thing to do. You're inferring characteristics about an object many light years away, and there's also a bit of a grey area between whether a massive object is a large planet or a small brown dwarf. HD 100546 is a star 316.4 light years from Earth that's orbited by a planet approximately 20 times the mass of Jupiter. The boundary for becoming a brown dwarf is around 19 times Jupiter's mass, putting this object well into the grey area. There are at least three other stars that are orbited by known brown dwarfs – substellar objects large enough to begin hydrogen fusion but not to sustain it. They gradually cool and darken over time, but while hot, they can see a rain of molten iron on their surfaces thanks to atmospheric convection.

> "HD 100546 is orbited by a planet approximately 20 times the mass of Jupiter"

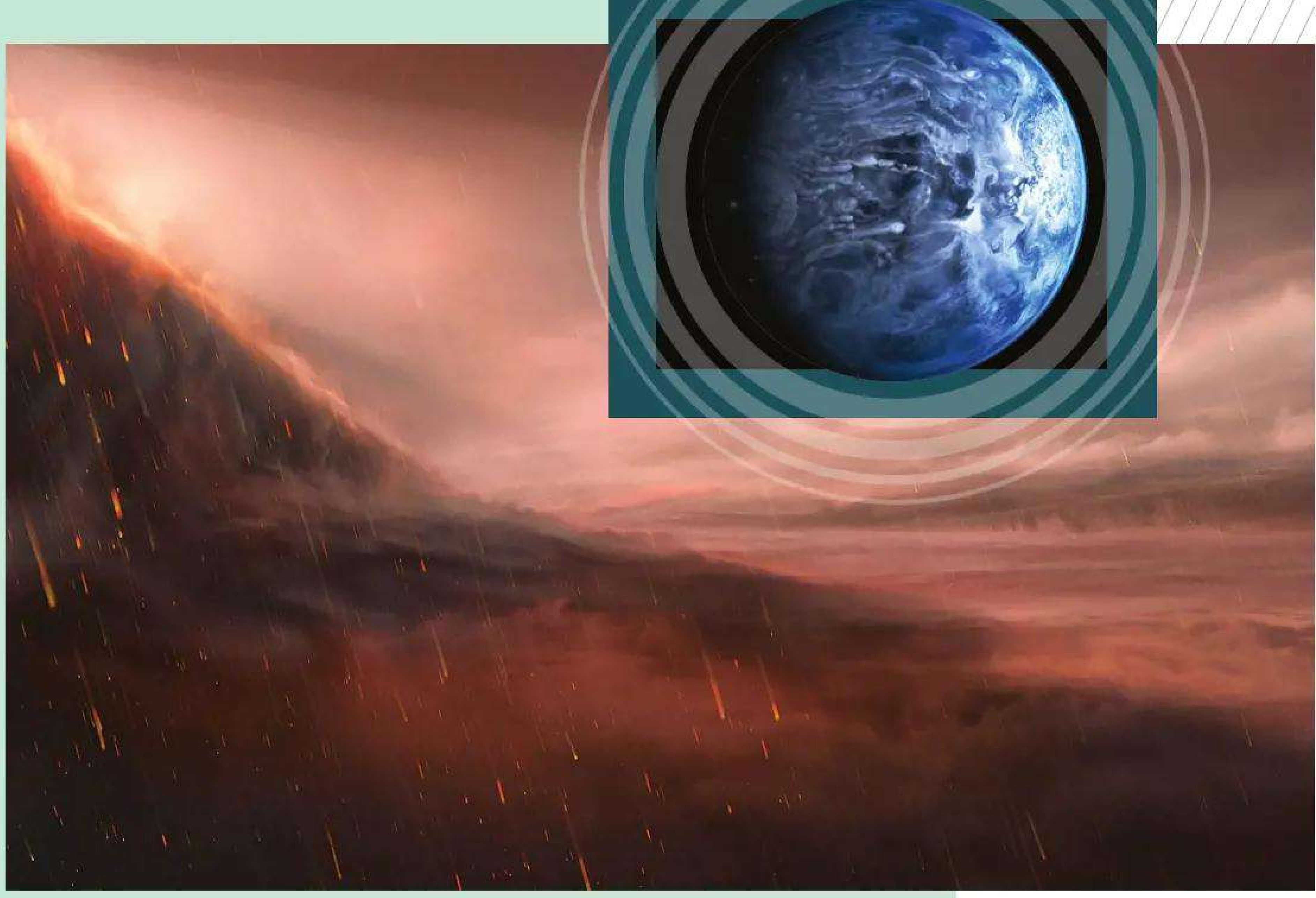
TOASTY TEMPERATURES

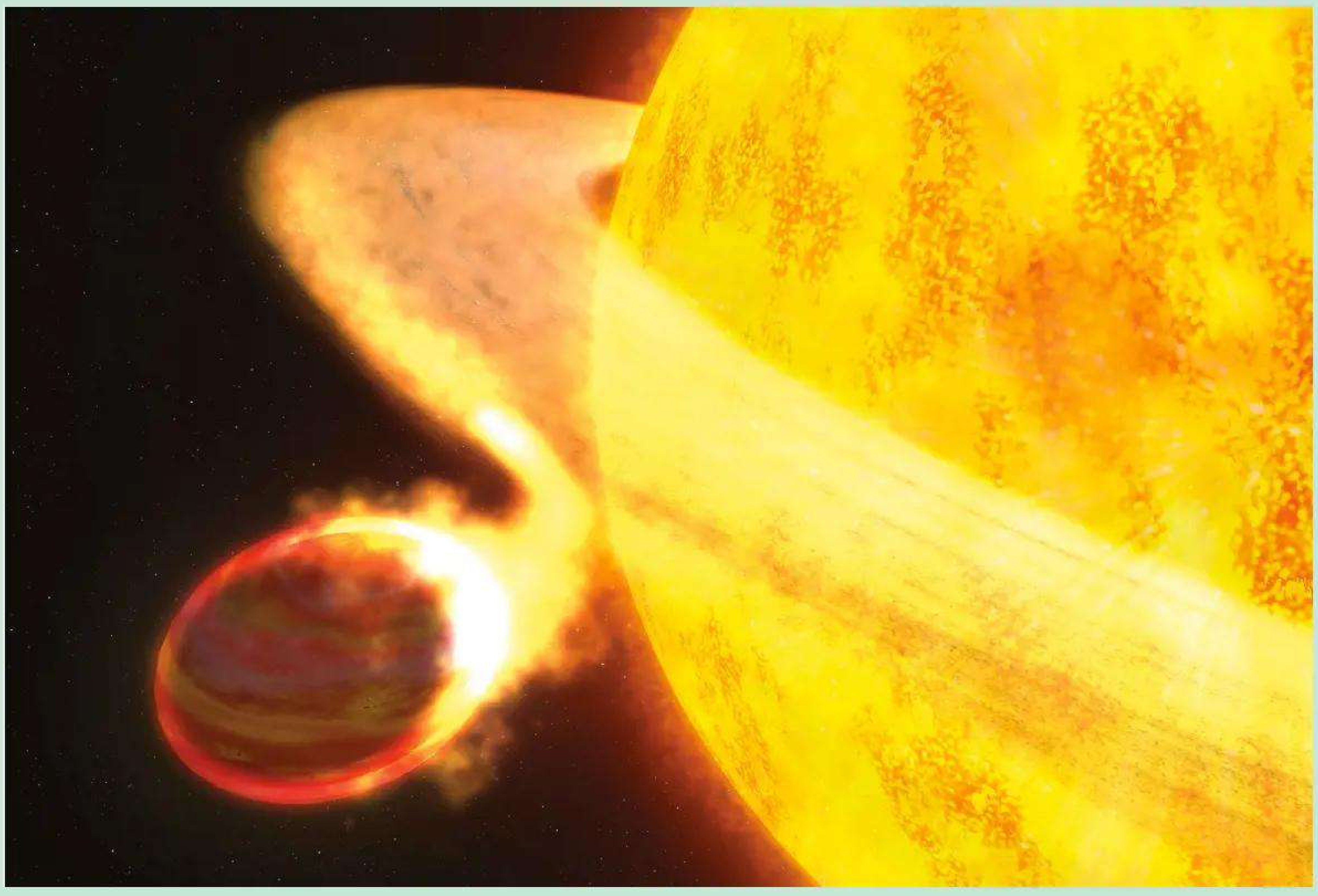
WASP-76 b was discovered in 2013, but an examination by the VLT in 2020 found that it's tidally locked. That means that, just like our Moon, one side of it constantly faces the body it orbits, in this case WASP-76, a yellow-white star in the constellation of Pisces. The planet, which is slightly less massive than Jupiter but almost twice as large, is very close to its star and orbits once every 1.8 days. Being tidally locked means one side of the planet receives an extreme amount of solar radiation, with a daytime temperature of more than 2,000 degrees Celsius (3,632 degrees Fahrenheit). Meanwhile, the nighttime side is a relatively balmy 1,000 degrees Celsius (1,832 degrees Fahrenheit). This difference in temperature means metals, vaporised by the high temperatures on the dayside, could be carried across to the night side and turn into dense clouds of aluminium, iron or magnesium.

RAINING DOWN MOLTEN GLASS

Exoplanets don't tend to have snappy names, so we're stuck with HD 189733 b for this one, which you'll find orbiting one half of a binary star system in the constellation of Vulpecula. It was first discovered in 2005 by a team of French astronomers, but more recent observations using the Spitzer Space Telescope and the VLT have shown that not only is the planet a rather pretty blue colour, its weather might be wild.

HD 189733 b is a 'hot Jupiter', a planet similar in size to the largest member of our Solar System that orbits close to its parent star, an orange dwarf, pushing up its temperature. Visitors to this planet can expect winds of up to 8,690 kilometres (5,400 miles) per hour, scorching temperatures, and a silicon-enriched atmosphere, leading to horizontal rain made of molten glass.



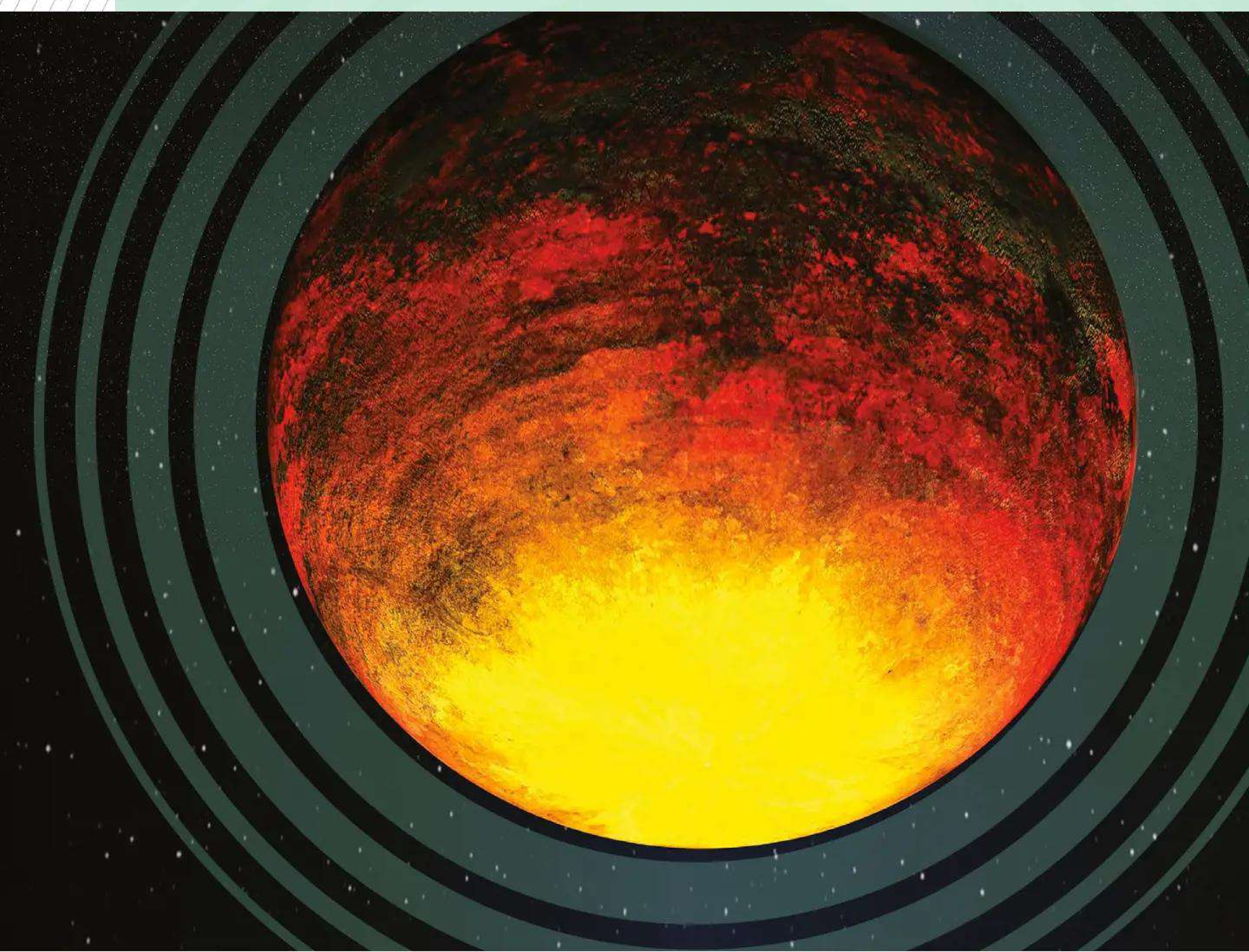


THE PLANET THAT'S LUNCH FOR ITS STAR

WASP-12 b's proximity to its star means it's sort of egg-shaped, as layers of its atmosphere are stripped away to feed the ever-hungry fusion furnace burning nearby. The Hubble Space Telescope spotted this cosmic meal in 2010, but further research has turned up many more interesting things. The planet, which is about twice the size of Jupiter, has one of the lowest densities seen in an exoplanet yet, as this gas giant's atmosphere has been pulled out by gravitational forces to be three times larger than our Solar System's giant planet's. The planet orbits its star in just over one Earth day, but eventually WASP-12 b's orbit will decay completely and it will fall into the star, though this will not happen for an estimated 10 million years.

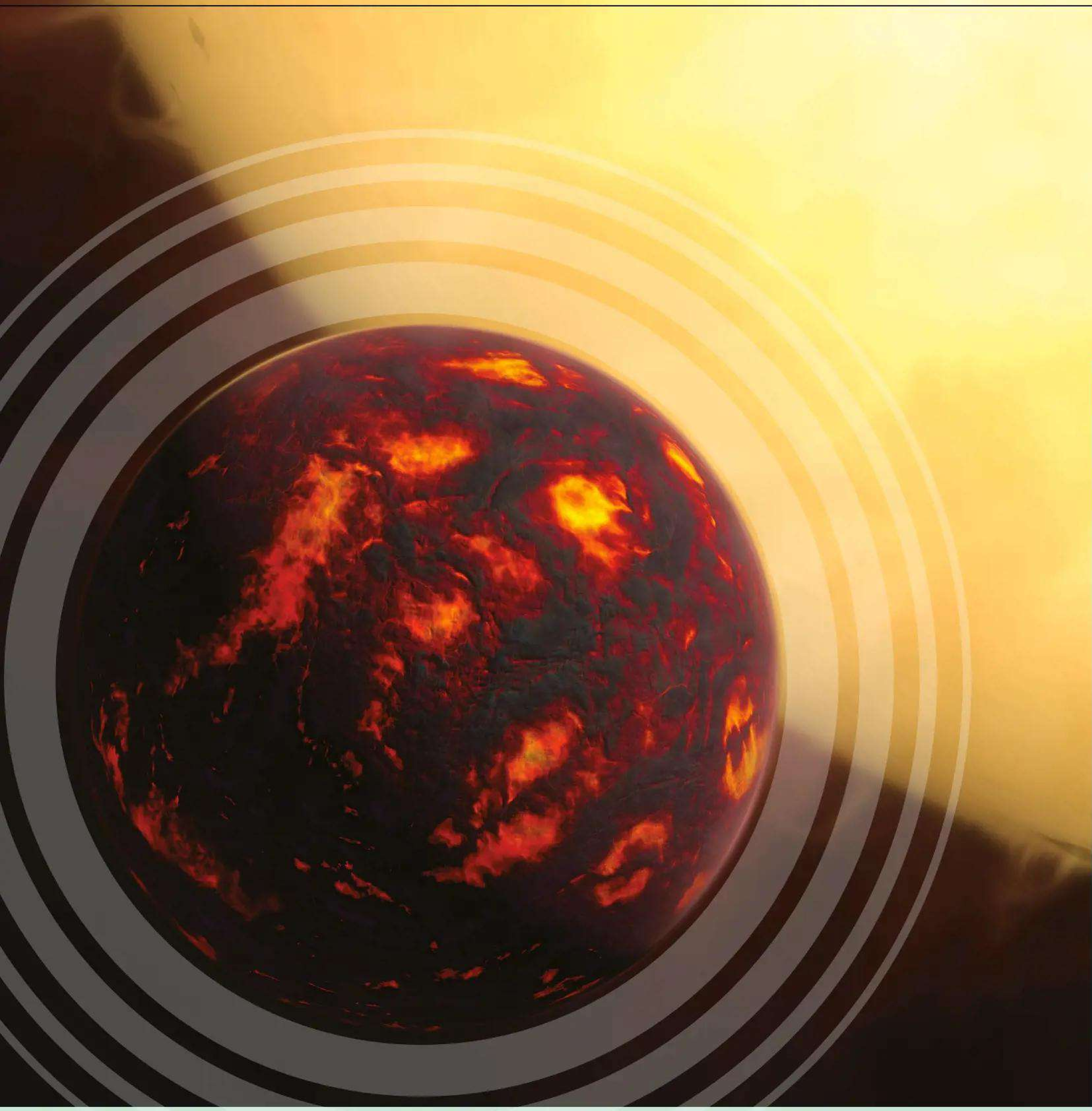
THE DIAMOND WORLD

There's a category of exoplanets known as 'super-Earths' that describes rocky planets less massive than gas giants but heavier than our own blue marble. 55 Cancri e is a good example. Orbiting a Sun-like star in a binary system 41 light years away, this world was the first super-Earth discovered around a main-sequence star. Situated so close to its star that each orbit takes just 17 hours, temperatures of 3,500 degrees Celsius (6,332 degrees Fahrenheit) are postulated. The planet has been inspected by two space telescopes: Hubble detected hydrogen and helium, but no water, while Spitzer's infrared view suggested a global lava ocean and volcanic activity. Strangest of all, the planet appears to be rich in carbon, which means one-third of it could be made of diamond.



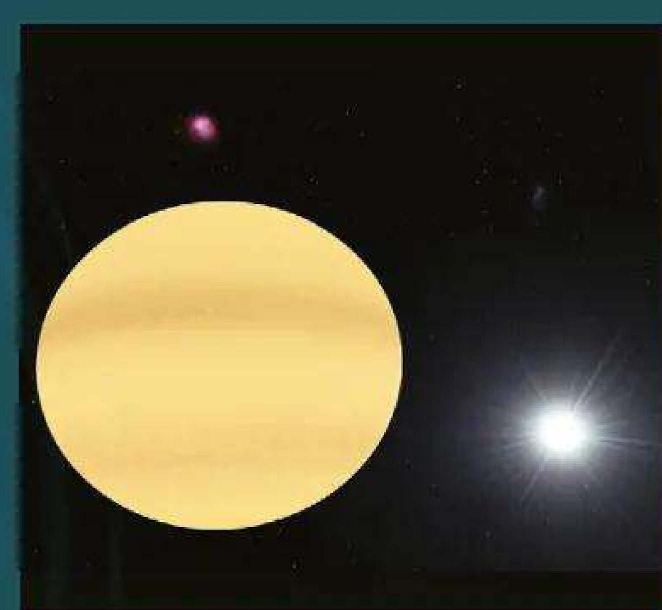
A WORLD OF LAVA

Some exoplanets are named after the telescopes that discovered them, as with the Kepler series of planets. This one, which orbits a Sun-like star in the constellation of Draco over 600 light years away, has a nickname: Mustafar. If that doesn't mean anything to you, brush up on your *Star Wars* lore. The volcanic planet where Obi-Wan Kenobi duelled Anakin Skywalker has an analogue out in the universe in Kepler-10 b, the first terrestrial planet found outside the Solar System. About 1.5 times the size of Earth but three times as massive, Kepler-10 b orbits fast and close and is tidally locked, with temperatures hot enough to melt iron and possibly a rocky surface. Its high reflectivity could be due to oceans of magma.



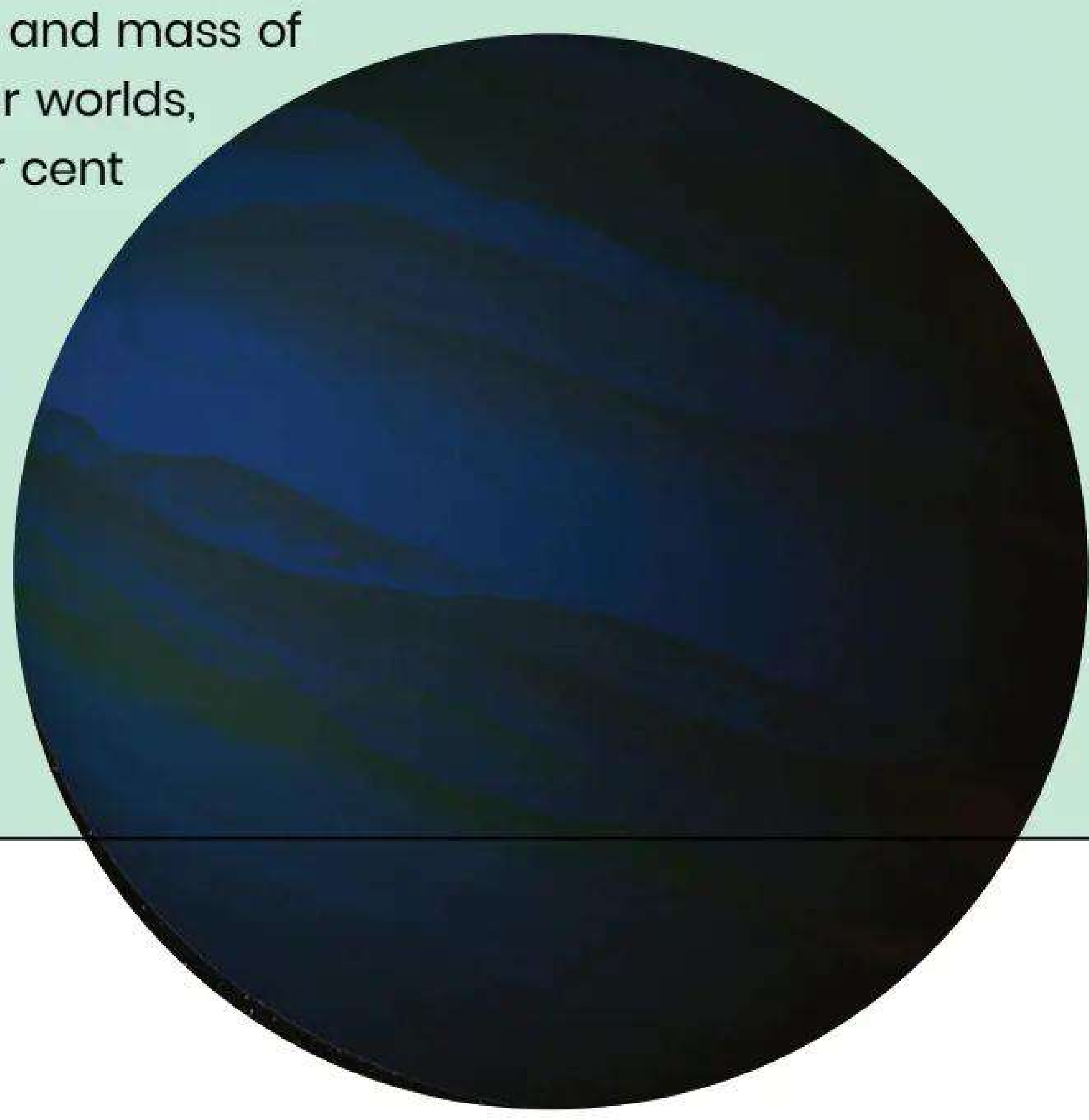
THE YEARS SPEED BY

The short, 17-hour year of 55 Cancri e might seem fast, especially if you're starting to feel like time on Earth is speeding up as you get older, but it's nothing compared to the length of a year on planet PSR J1719-1438 b. It makes its home around a pulsar that flashes once every 5.8 minutes in the constellation of Serpens Cauda. At 4,000 light years away, it's a tricky place to study in detail, and it has been theorised by one astronomer that it could be something more exotic than a star – like a lump of quark matter with the mass of Jupiter. Its planet is slightly more conventional, but it's still an extreme world. At the time of its discovery, it was the densest exoplanet ever seen, being four times the size of Earth but 330 times heavier. It also orbits so closely to its star that a year on PSR J1719-1438 b lasts just 2.17 hours, and the star and planet's orbit would fit inside our Sun.



THE DARK PLANET

Hot Jupiters are among the most commonly identified exoplanets, not only because they're large, but their tight orbits around their stars mean they whip around them at speed, giving more data for the radial velocity method of detecting them via wobbles in the stars themselves. TrES-2 b, which orbits a yellow Sun-like star that's part of a binary in Draco once every 2.5 days, is one such planet, about 1.2 times the radius and mass of Jupiter. What sets it apart from other similar worlds, however, is that it reflects less than one per cent of the light that hits it. This exceptional lack of brightness means it's darker than coal. It's theorised to be due to a lack of clouds in its atmosphere, which would reflect more sunlight as they do on Saturn or Venus, or the presence of light-absorbing chemicals such as sodium, potassium or titanium oxide.

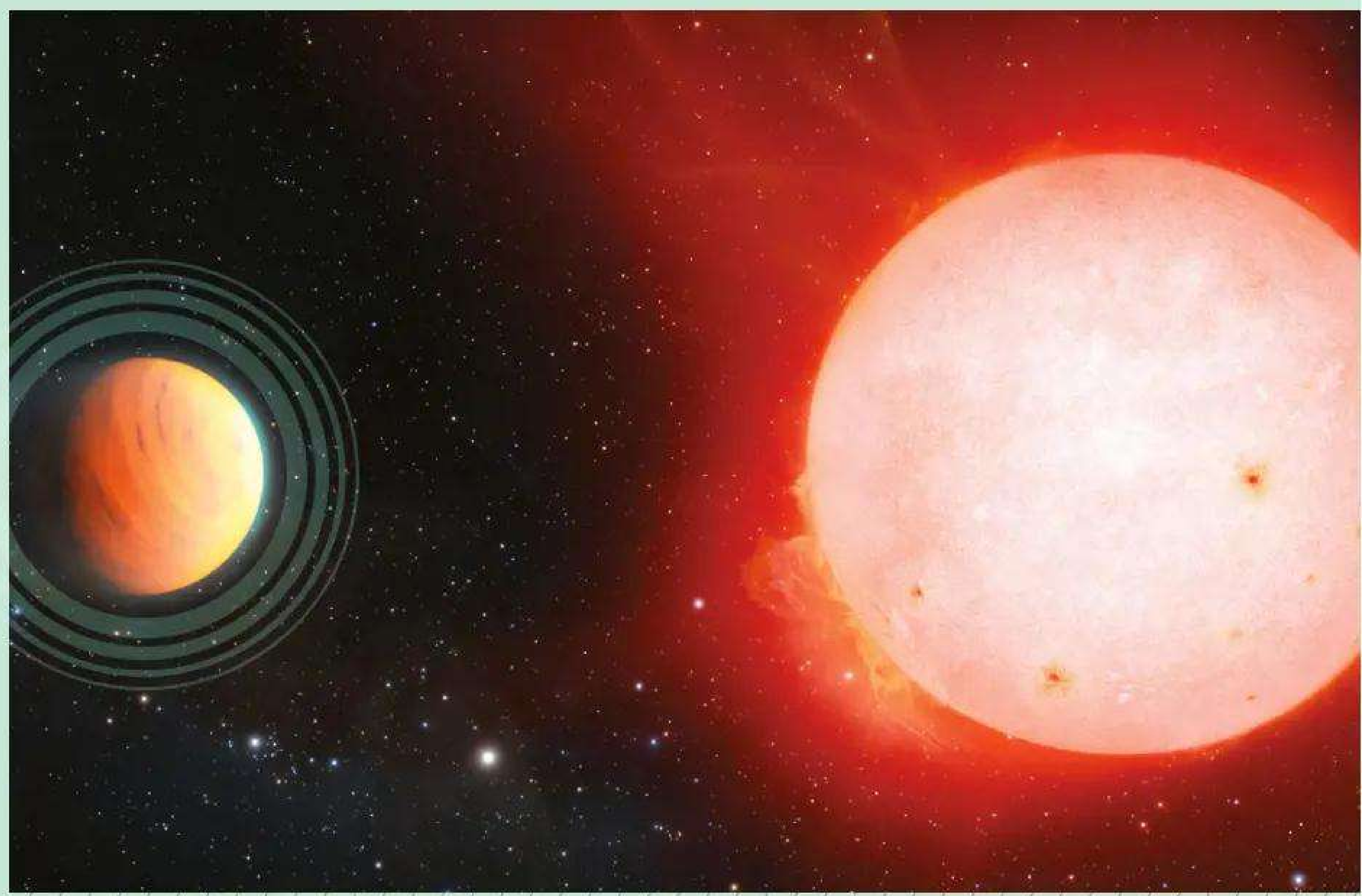


VAST RINGS

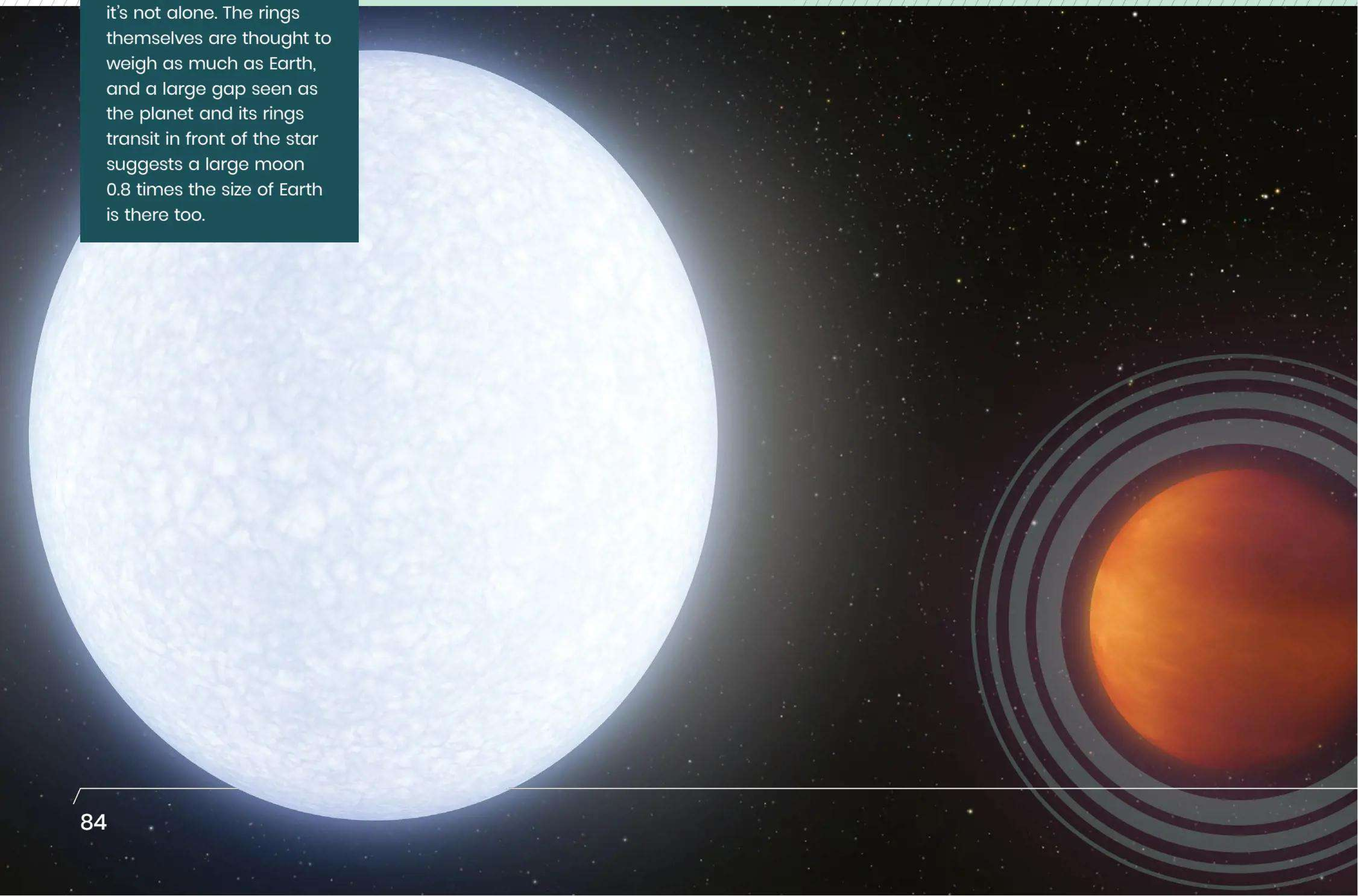
Orbiting the young star V1400 Centauri, 1SWASP J1407 b could be either a large gas giant or a brown dwarf. What's more certain is that it has an extensive ring system, approximately 200 times larger than that found around Saturn. The planet takes around a decade to orbit its star, though its path seems to be eccentric. The star's output is variable, making detection harder. With a mass between 13 and 26 Jupiter masses, there's considerable uncertainty about what exactly the planet is, but gaps in its ring system suggest it's not alone. The rings themselves are thought to weigh as much as Earth, and a large gap seen as the planet and its rings transit in front of the star suggests a large moon 0.8 times the size of Earth is there too.

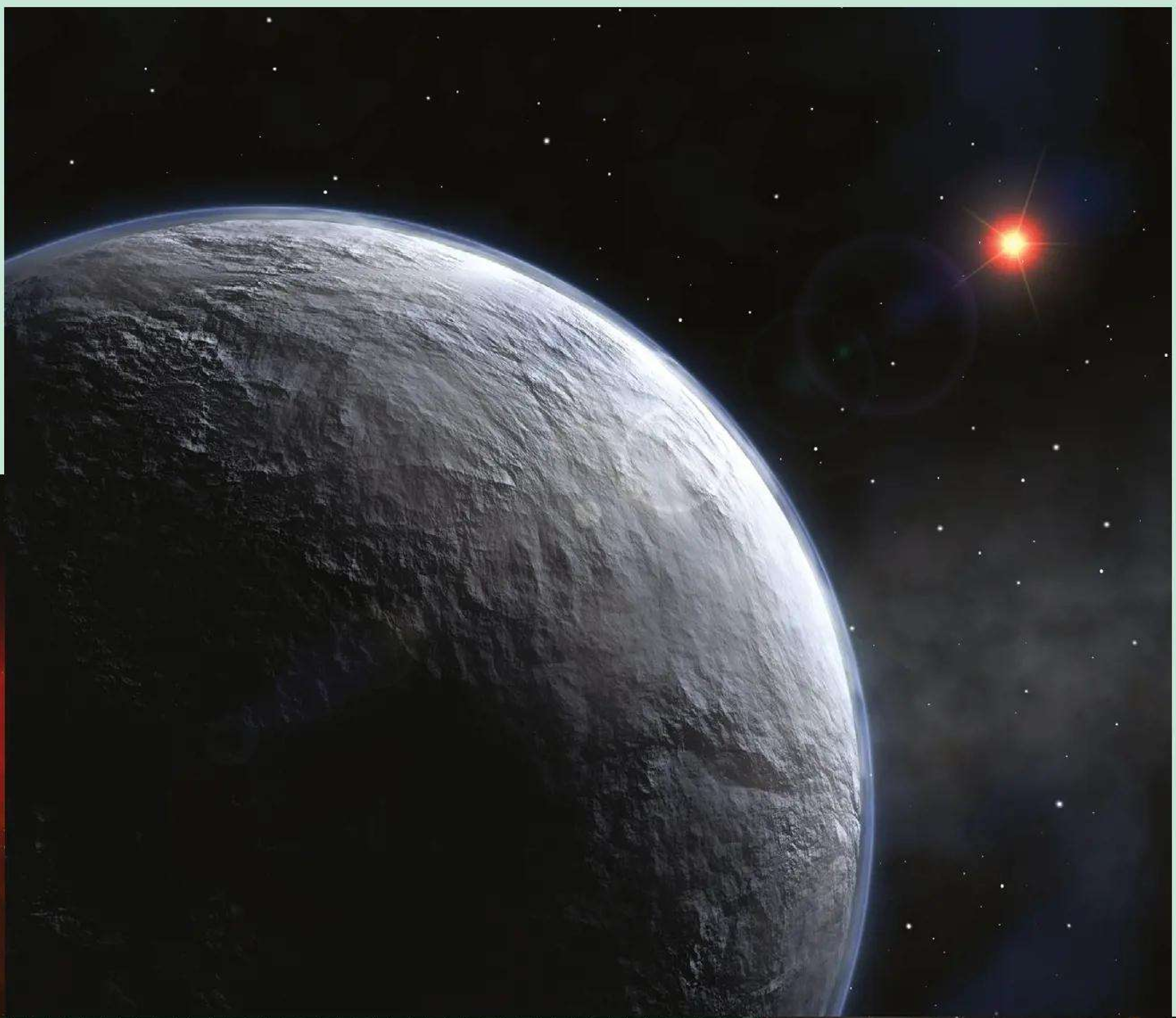
FLUFFIEST PLANET EVER

When we say fluffy, we don't mean like a chinchilla, but more like a marshmallow. TOI-3757 b is 580 light years away in the constellation of Auriga, orbits a cool red dwarf star and has an average density similar to that of a campfire-toasted treat. The planet is a gas giant slightly larger than Jupiter, but only a quarter of its mass. TOI-3757 b orbits its star in 3.5 days. Its solar system has less of the heavy elements you'd usually find around such a star, which means it probably formed more slowly than other planets, pulling in less gas around its rocky core and becoming less dense as a result. It also has an elliptical orbit, bringing it very close to its star and causing its atmosphere to expand due to the intense heat.



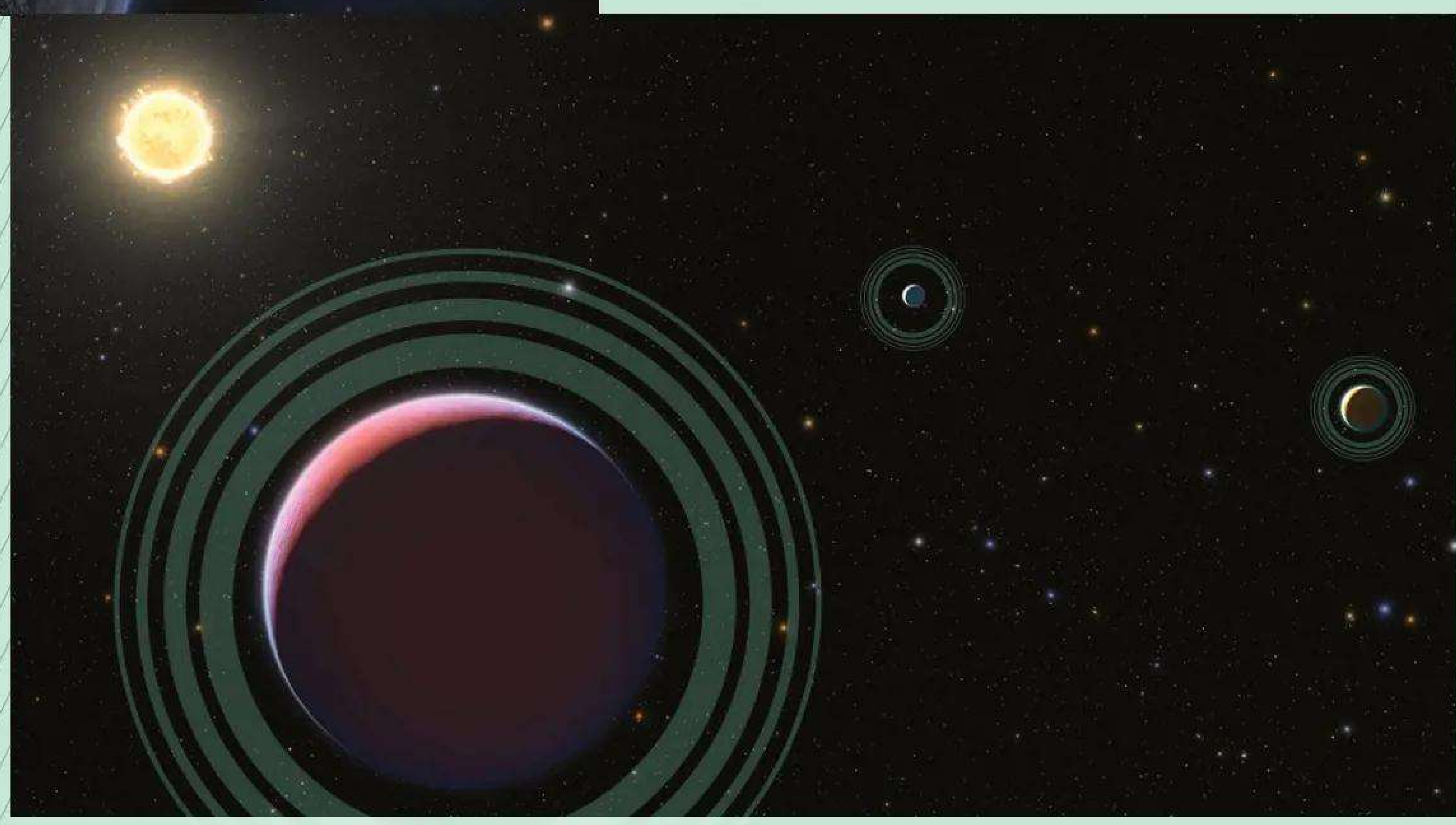
"The planet is a gas giant slightly larger than Jupiter, but only a quarter of its mass"





A GIANT SNOWBALL

OGLE-2005-BLG-390L b can be found 21,500 light years away in Scorpius orbiting a dim red dwarf star and is about five times the mass of Earth. The low output of the star – as well as the fact the planet orbits between two and four times the distance between Earth and the Sun, which would put it beyond Mars, around the same distance as the asteroid belt – means it's significantly cooler, with a surface temperature of around -220 degrees Celsius (-364 degrees Fahrenheit). It takes about ten Earth years to complete an orbit, and it's small, with only about a quarter of the mass of Earth. Such is its chilliness that NASA has given the planet the nickname 'Hoth' after the ice planet from *Star Wars*.



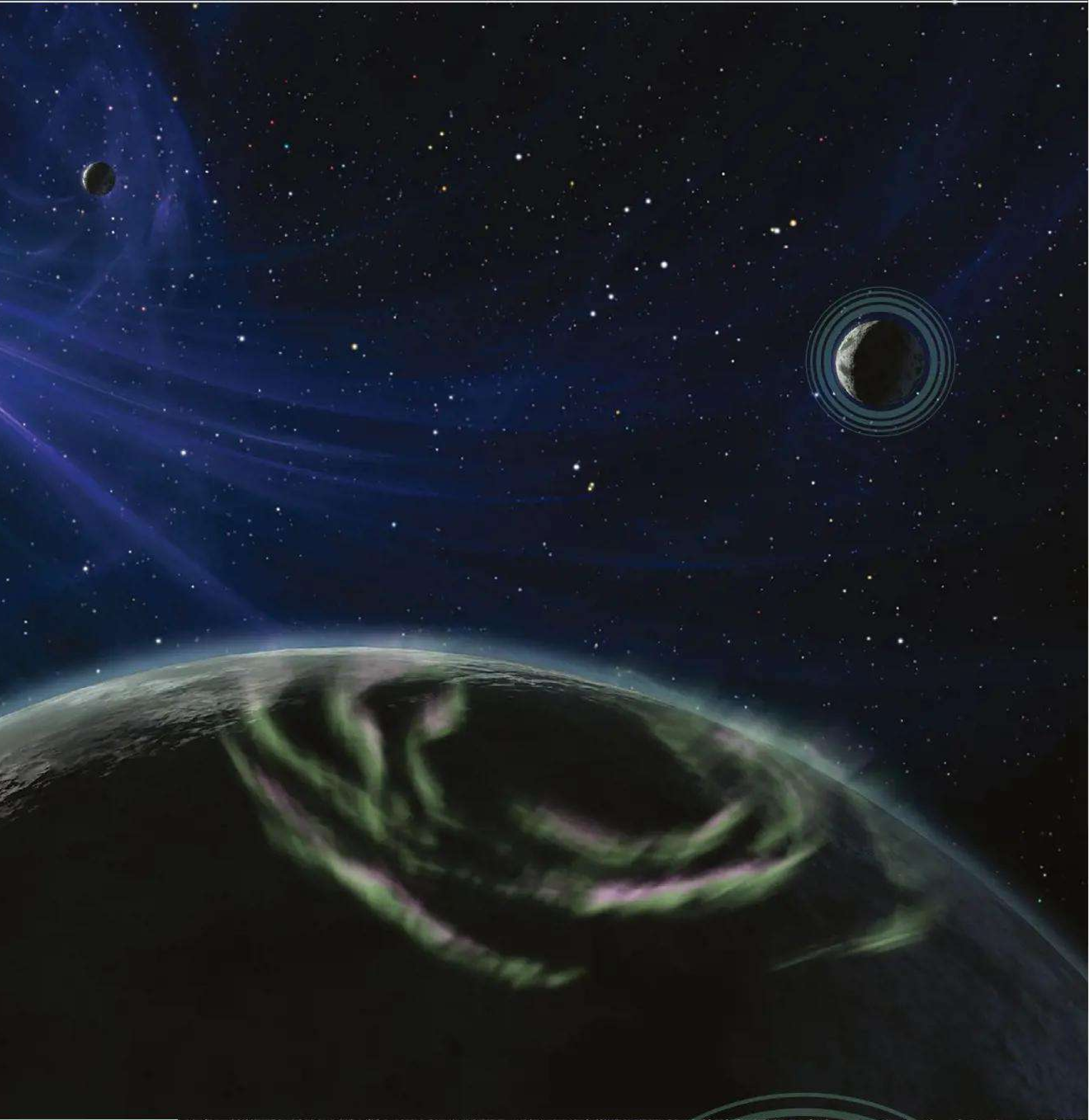
BOILING HOT

We've had some hot planets on this list, with surface temperatures in the thousands, but nothing beats KELT-9 b. It takes the definition of a hot Jupiter and tears it up, hitting 4,300 degrees Celsius (7,772 degrees Fahrenheit) – hotter than some stars. And when you're this close to your home star, every day is sunny. KELT-9 b orbits a B-type star that's twice as hot as our Sun – the first such star known to have a planet. The planet is tidally locked, orbiting so close that its year lasts just one-and-a-half Earth days. It's so hot there that molecules on the planet's surface are broken into their constituent atoms, and its atmosphere is slowly escaping, leading to a giant tail of superheated gas behind it as it zooms around its star.

A TRIO OF GIANTS

Not one exoplanet, but three, Kepler-51 is a young Sun-like star in the constellation of Cygnus that's otherwise unremarkable but for its trio of extremely low-density gas giants. These diaphanous globes are barely there, more like expanded polystyrene than planets as we know them. They've been named 'super puffs' – having a mass just a few times greater than Earth's but similar in size to Jupiter, their material is extremely stretched out and thinly packed. They all have short years, from 45 to 130 days, and their low densities are likely a consequence of their young age – they formed as icy worlds further out in the system and have migrated inwards, so their gases are now boiling off in the warmer conditions found there. Alternatively, but much less likely, they could be smaller planets with enormous ring systems.

THE STAR THAT SPINS



Our Sun, as giant fusion reactors go, is quite placid, only troubling us occasionally with coronal mass ejections and solar flares. The three planets orbiting PSR B1257+12, however, have much more of a problem, as their star is a pulsar. The rapidly spinning neutron star at the centre of this star system, located 2,300 light years from the Sun in the constellation of Virgo, has a radius of just ten kilometres (6.2 miles) but a mass greater than that of the Sun, rotating around 160 times a second. Most of the bodies in the system have been named after undead creatures: the star is known as Lich, while two of its planets are Draugr and Poltergeist. The third planet is Phobetor, one of the sons of Somnus, the personification of sleep in Ovid's *Metamorphoses*. Only four other pulsars are known to have planets, making this system a rarity in the visible universe.

A WORLD OF ICE AND FIRE

44 light years away from us, Upsilon Andromedae b is a tidally locked planet that orbits its Sun-like star in less than five days. It's notable for the extreme difference in temperature between its day and night sides. It has a tight orbit, taking 4.6 days to complete a trip around its sun, and is a gas giant with about 1.8 times the mass of Jupiter. Infrared observations with the Spitzer Space Telescope showed that the star-facing side of the planet is around 1,500 degrees Celsius (2,732 degrees Fahrenheit) – hot enough to melt rock – while the nightside could be as cold as -20 degrees Celsius (-4 degrees Fahrenheit) and even have snow, as water vapour has been detected in the planet's atmosphere along with clouds of metal oxides.

THE WANDERER

This enormous gas giant, three times the size of Jupiter, can be found orbiting a Sun-like yellow star 102.7 light years away in the constellation of Virgo. But it's the orbit of this planet that sets it apart from many others. While we've seen exoplanets tucked in close to their stars and a few in the habitable zone or beyond, HR 5183 b is highly eccentric. Its orbital track brings it as close as 2.9 astronomical units to its star – one astronomical unit being the distance from Earth to the Sun – but also flings it as far as 42 astronomical units away over a period of around 100 years. No planetary orbits are completely circular, but the huge eccentricity in its orbit has earned the planet the nickname 'the whiplash planet'.

THE PLANET WITH TWO ATMOSPHERES

You don't need to go far to reach this extreme exoplanet, just 41 light years or so, but when you get there you might not like the smell. Gliese 1132 b is a rocky planet orbiting a small red dwarf in the constellation of Vela. It's a bit bigger than Earth and is close to its star, so a year lasts just 1.6 days. Despite receiving 19 times as much radiation from its star as Earth does, it's managed to hold onto its atmosphere, with a thick layer of methane and hydrogen cyanide pumped out of volcanoes. These are caused as the planet flexes as it orbits its star, pushing gases up to the surface. The planet has a surface temperature hotter than Venus, and the volcanic gases are replacing the original atmosphere of hydrogen and helium that was left over from the planet's formation.

THE PLANET IN ANOTHER GALAXY

M51-ULS-1 b is an exoplanet candidate in the Whirlpool Galaxy, a whopping 28 million light years away. Given the distance, we know a surprising amount about it. NASA's Chandra X-Ray Observatory was watching the X-ray emissions of a binary system comprising one large star and an object that may be a neutron star or small black hole when it spotted the telltale dip in intensity that occurs when an orbiting body passes between the emitter and observer. From this, scientists were able to work out that it's probably a planet slightly smaller than Saturn and orbits at a distance similar to Saturn or Uranus from our Sun.

"Scientists were able to work out that it's probably a planet slightly smaller than Saturn"

THE ONE MOST LIKE EARTH

Teegarden b ticks a lot of the right boxes as far as potential habitability is concerned. In the Earth Similarity Index, a way of classifying exoplanets that takes into account size, density, gravity, temperature and other characteristics to provide a measure of how similar a planet is to Earth, this distant world, 12.5 light years away in Aries, sits at the top. That's no guarantee of habitability, though. Teegarden's Star is a red dwarf one-tenth the size of our Sun, which is only just large enough to become a star and not a brown dwarf. This lack of light output means its habitable zone is much closer than that of our Sun, and Teegarden b has a year that lasts just five Earth days. However, it's approximately Earth-sized, likely to be rocky and has a 60 per cent chance of being home to liquid water. But according to astronomers, there's only a three per cent chance of it having an atmosphere.

MYSTERIES OF THE UNIVERSE

HOW DO SUPERMASSIVE BLACK HOLES FORM?

Astronomers have discovered a supermassive black hole that existed 470 million years after the Big Bang, and it's proving to be enlightening

Reported by David Crookes

Supermassive black holes range from hundreds of thousands to billions of times the mass of our Sun, and they're thought to be at the centre of almost every large galaxy in the universe. But while scientists know plenty about them despite having only confirmed a handful, quite how they formed remains something of a mystery. They puzzle astronomers because some are known to have formed very early in the universe's life. While most black holes are created out of the remnants of a large star dying in a supernova explosion when it reaches the end of its life and collapses under its own gravity, this doesn't explain how supermassive black holes emerged less than 700 million years after the Big Bang – and how they became so colossal. There just wouldn't have been enough time for these huge black holes to form.

A recent discovery may go some way towards a better understanding of how some supermassive black holes were able to form and reach such a great mass so early in the universe's life. By making use of the James Webb Space Telescope, astronomers have been able to locate a distant galaxy called UHZ1 in the direction of the galaxy cluster Abell 2744, which is nicknamed Pandora's Cluster. With the aid of the Chandra X-ray Observatory, they have been able to find the most distant black hole ever seen in X-rays and make some startling discoveries.

If nothing else, the study – which involved Ákos Bogdán of the Harvard-Smithsonian Center for Astrophysics, Andy Goulding of Princeton and Priyamvada Natarajan, chair of the department of astronomy at Yale – has shown the immense power of NASA's telescopes. In particular, it's proving once more why Webb, which entered service in July 2022, is worth every cent of its multi-billion-dollar construction. But it's also shedding fresh light on what we know about black holes and how there is now a new class of distant objects. "The detection of this black hole was part of a dedicated observing campaign," Bogdán tells **All About Space**. "Webb observed Abell 2744 in multiple observing programs with the goal of identifying galaxies in the early universe. We built our Chandra observing program on these Webb observations. The goal of the Chandra program was to detect accreting supermassive black holes in galaxies that were identified by Webb."

Being able to spot UHZ1, which has a mass around 140 million times the mass of the Sun, in the direction of Pandora's Cluster proved to be something of a breakthrough and a triumph for cutting-edge technology. That's because the Abell 2744 cluster – located 3.5 billion light years from Earth in the constellation of Sculptor and formed out of four smaller

An artist's impression of what a supermassive black hole would look like at the heart of a galaxy

BLACK HOLES BY NUMBERS

100,000+
Solar masses needed to define a supermassive black hole

THREE
The number of black hole types: stellar, intermediate and supermassive

10 to 100 million solar masses
The mass of UHZ1's supermassive black hole

13.2 billion
Distance, in light years, of UHZ1 from Earth

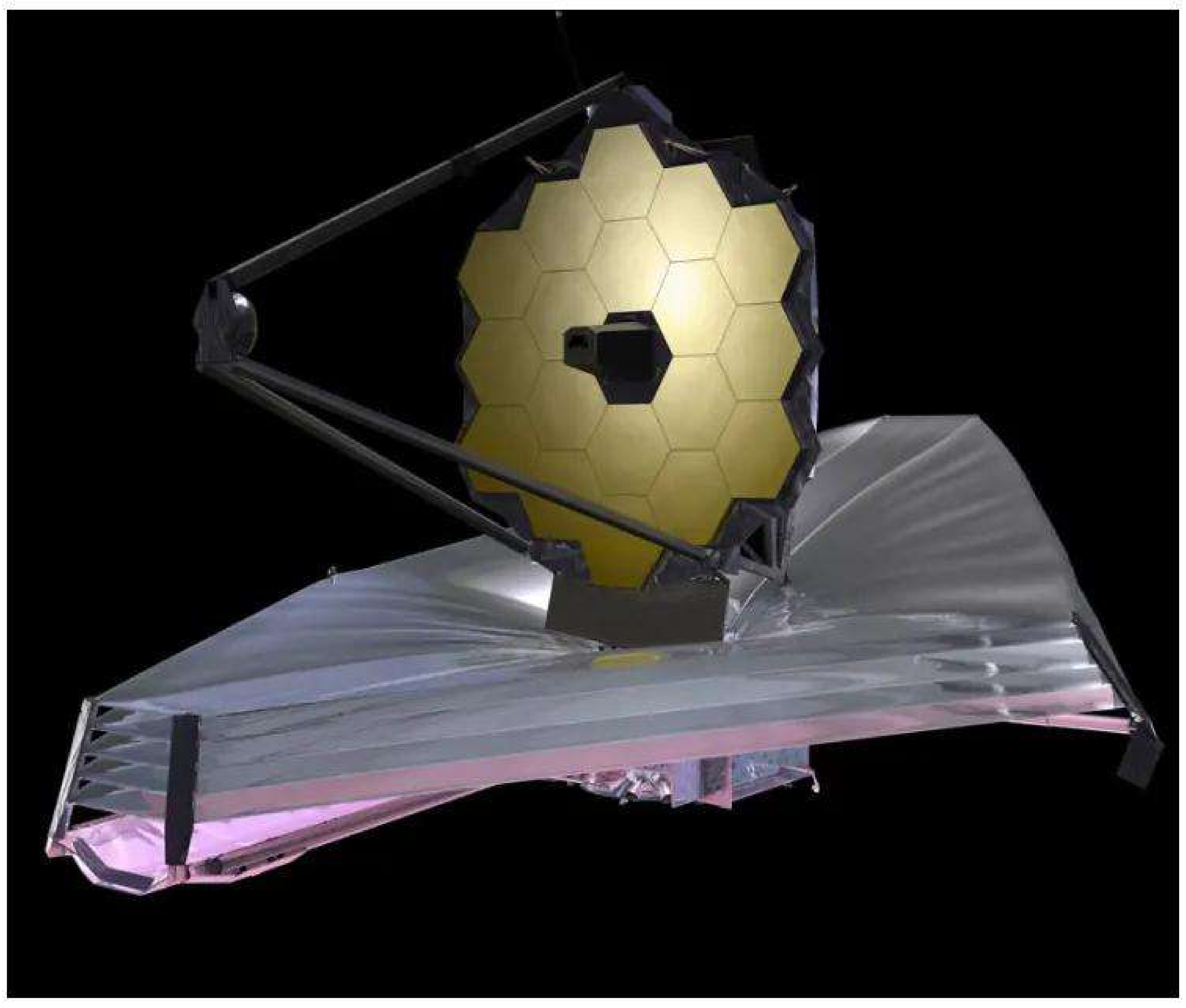
4 million
Solar mass of Sagittarius A* at the centre of the Milky Way

26,760
Distance, in light years, to Sgr A* from Earth

ONE
The number of supermassive black holes in a galaxy

40 trillion
The potential number of black holes in the universe

galaxy clusters over a period of 350 million years – is so dominant in that part of the sky. In fact, it's 4 million light years across, with a mass of 4 trillion Suns. But Webb has still been powerful enough to allow the UHZ1 galaxy's faint light to be seen, and it went further back than many imagined. "Webb had an important role in this discovery, as it identified the galaxy and told us where we should look with the Chandra X-ray Observatory to search for a supermassive black hole," Bogdán explains. "Prior to the launch of Webb, these extremely young galaxies could not have been observed. The near-infrared sensitivity and the large collecting area of Webb made it possible to peek into the early universe and detect galaxies shortly after the Big Bang, such as UHZ1."

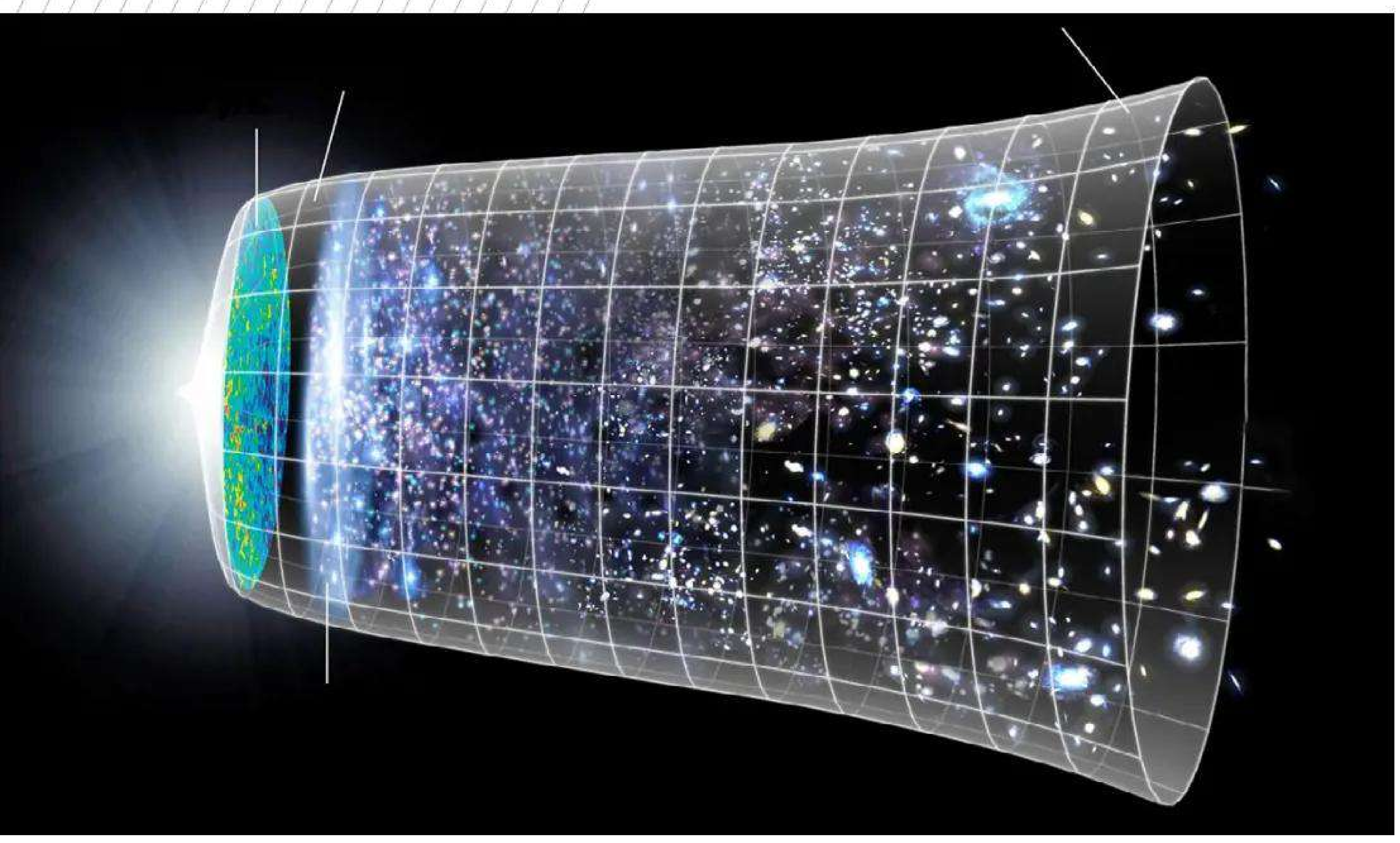


Once Webb located the galaxy, it was able to divulge more information about it, including the important revelation that the galaxy was actually more distant than the cluster. Since UHZ1 has a redshift of 10.1 – a number which indicates the increase in the wavelength of light emitted by distant objects as they reach Earth – the galaxy is around 13.2 billion light years away. It formed when the universe was just three per cent of its current age. Webb was able to make its observations using a technique called gravitational lensing, which used the gravity of Abell 2744 to amplify UHZ1's light. This paved the way for observations to be made using Chandra, with the data from both telescopes combined giving a clearer picture of the distant galaxy – and a supermassive black hole within it.

"Gravitational lensing is essentially a cosmic magnifying glass," Bogdán explains. "It magnifies light coming from all wavelengths and helps us collect more photons from the galaxy. This was especially critical for the Chandra observations. In the case of UHZ1, the lensing magnification is about a factor of four – that is, we observe four times more photons than we would have observed without the lensing effect. Without this substantial lensing magnification, we would not have been able to conclusively detect the supermassive black hole associated with UHZ1."

To detect the growing supermassive black hole, which now takes its place as the oldest known X-ray quasar – a luminous supermassive black hole – Chandra was used to observe UHZ1 for two weeks, picking up on a telltale sign: the presence of intense superheated X-ray-emitting gas at the distant galaxy's core. Since no supermassive black hole has ever been seen at this stage of growth before, it has hugely excited the researchers, who have published a paper in *Nature Astronomy*. It has also gone a long way in backing up a relatively new theory about the formation of some black holes.

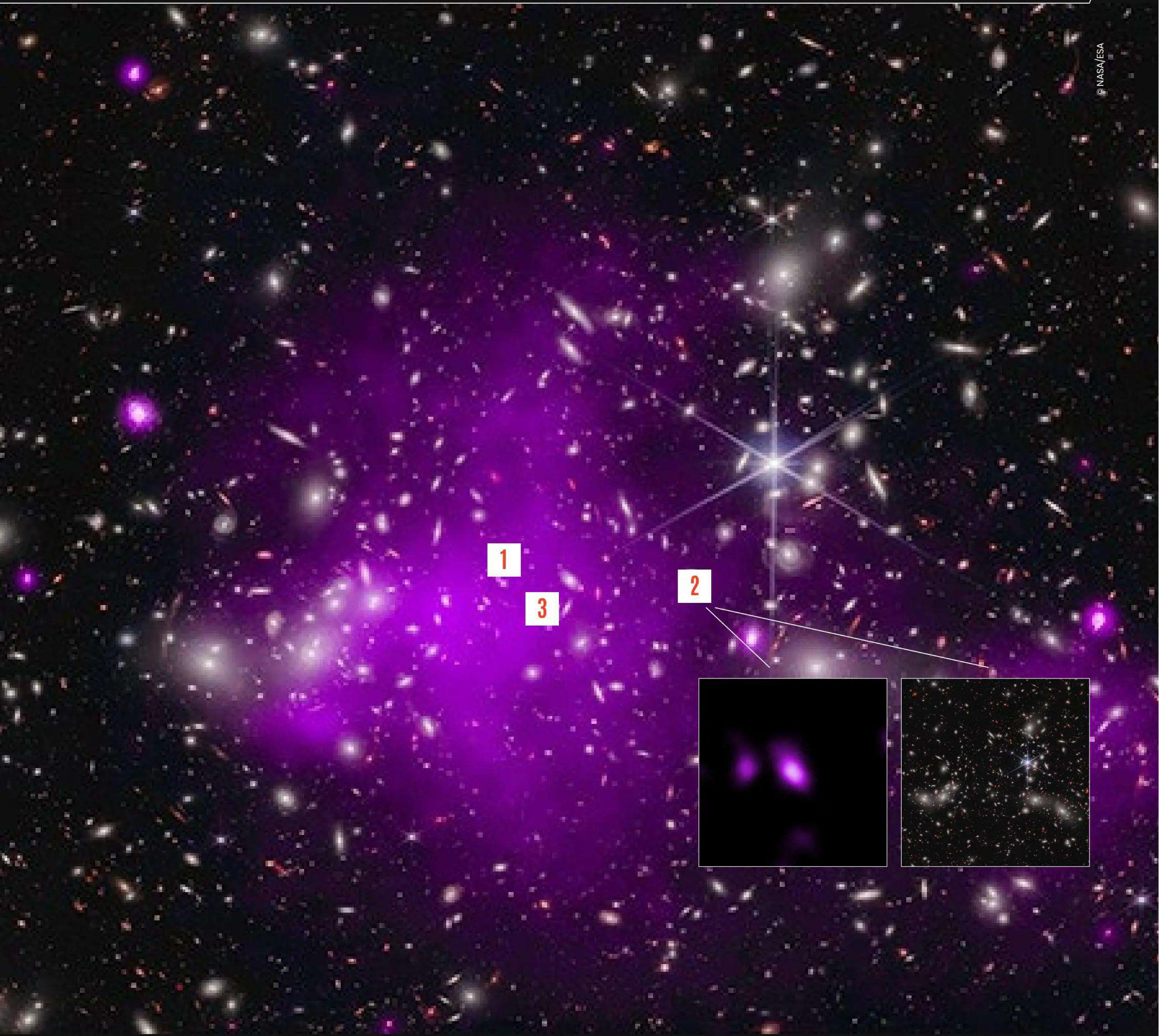
"Chandra was essential in detecting the supermassive black hole as it is sensitive to very high-energy photons, specifically X-rays," Bogdán says. "Growing supermassive black holes accrete gas through an accretion disc, in which gas gets heated to very high temperatures, emitting X-ray photons that are observable in the X-ray waveband. Chandra can detect these high-energy X-rays from rapidly growing black holes, which was the key measurement in the study. Based on the Chandra measurement, we could detect this rapidly growing black hole, and we also found that the supermassive black hole is surrounded by a substantial amount of gas, which obscures lower energy photons. Therefore, the black hole can be best observed in X-ray wavelengths, and in particular with Chandra."



The James Webb Space Telescope, designed to show the first stars that shone in the universe, was the first to spot distant galaxy UHZ1

The universe is believed to have begun with the Big Bang, and some supermassive black holes formed a short time after that

The overall data shows that the supermassive black hole is ten times larger than the one in the Milky Way. It has a mass between tens of millions to hundreds of millions of solar masses, which is actually equivalent to the mass of its host galaxy – a fact that astonished astronomers even more. Nobody really expected to ever see such a whopper of a supermassive black hole so early in the universe's creation, but there it is, taking astronomers a big leap forward in working out how they form. "The results were surprising; they were mostly



STRIKING EFFECTS

How NASA's telescopes combined to discover a distant black hole

1 Gazing into the distance

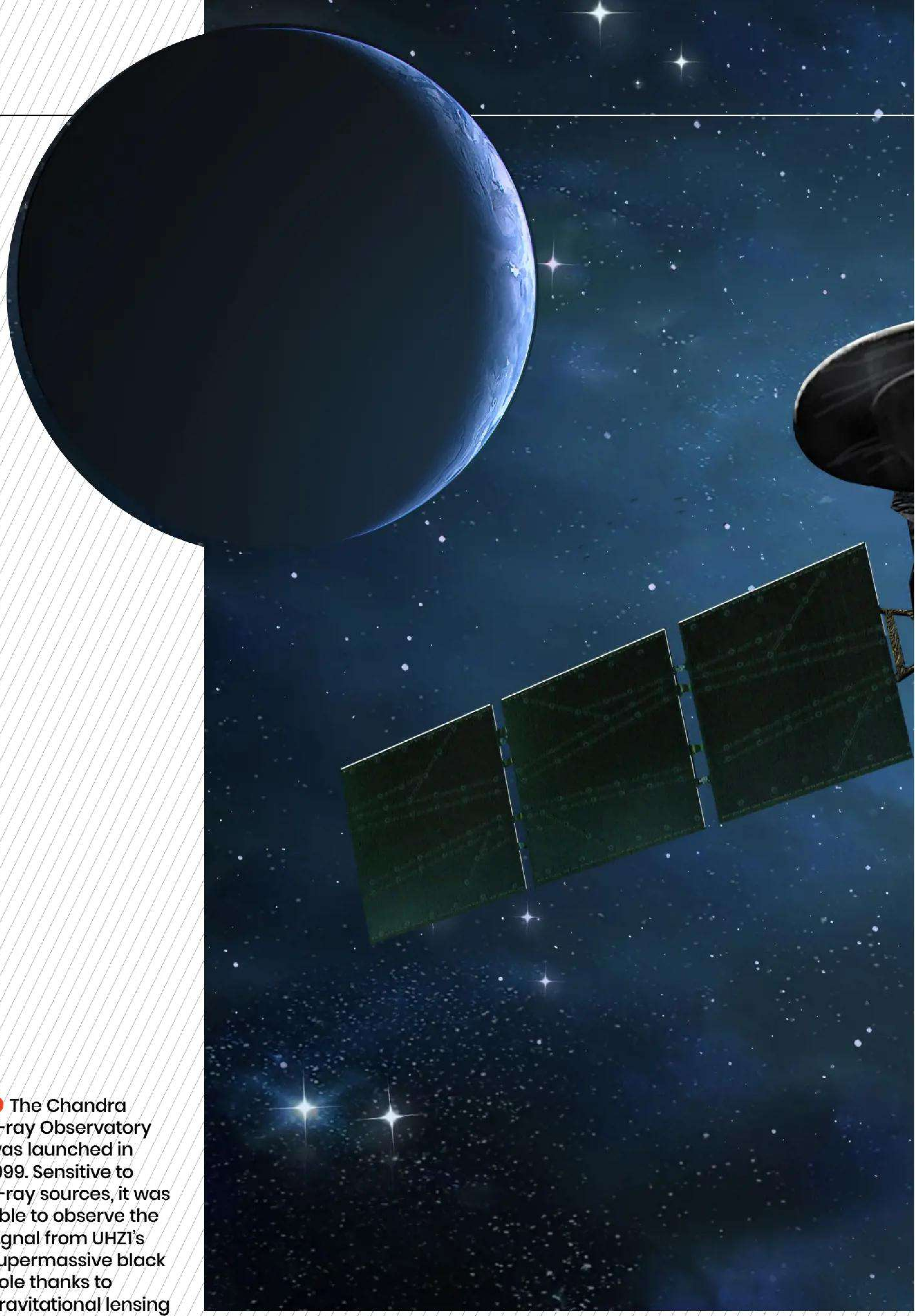
The James Webb Space Telescope was pointed in the direction of the galaxy cluster Abell 2744, which is 3.5 billion light years from Earth.

2 The black hole host galaxy

Using infrared data, Webb identified the galaxy UHZ1, which was much further away. It's some 13.2 billion light years from Earth, when the universe was just three per cent of its current age.

3 The black hole

Within UHZ1 is a growing supermassive black hole that is 5.5 million light years across, identified by its X-ray emissions using the Chandra X-ray Observatory.



surprising since we detected a black hole in a galaxy in the very early universe whose mass is comparable to the stellar mass of the galaxy itself," Bogdán affirms. "In the local universe, the ratio of black hole mass to galaxy mass is about 0.1 per cent. In other words, the stars in a galaxy are 1,000 times more massive than the black hole.

"This is not the case in UHZ1, where the black hole mass is about 10 to 100 per cent of the mass of the stars. The detection of a massive black hole merely 470 million years after the Big Bang, coupled with this very high black hole mass to galaxy mass, tells us critical information about how the first seed black holes may have formed and suggests that, in the case of UHZ1, it originated from the collapse of a massive gas cloud." In other words, it would appear that the supermassive black hole was born massive, which has given it a head start on so many other supermassive black holes in the universe.

"The main idea is that these black holes are born huge, with 10,000 to 100,000 times the mass of the Sun," says Bogdán. And it's this which places the recently observed supermassive black hole in the category of a new object class. "A theory that describes the black hole observed in UHZ1 is one called outsize black holes. According to this model, black holes form with huge masses early in the evolution of galaxies. For a short cosmic time, the mass of black holes can be comparable with the stellar mass of the galaxy. This is exactly what we see in the case of UHZ1."

The outsize black holes theory was pioneered by Natarajan and her research group. She said the early universe had heavy black hole seeds with large birth masses that likely formed from direct collapse in galaxies where star formation

The Chandra X-ray Observatory was launched in 1999. Sensitive to X-ray sources, it was able to observe the signal from UHZ1's supermassive black hole thanks to gravitational lensing

HOW DO EARLY SUPERMASSIVE BLACK HOLES FORM?

Astronomers have been pondering how they can reach such colossal masses

They were created when stars exploded

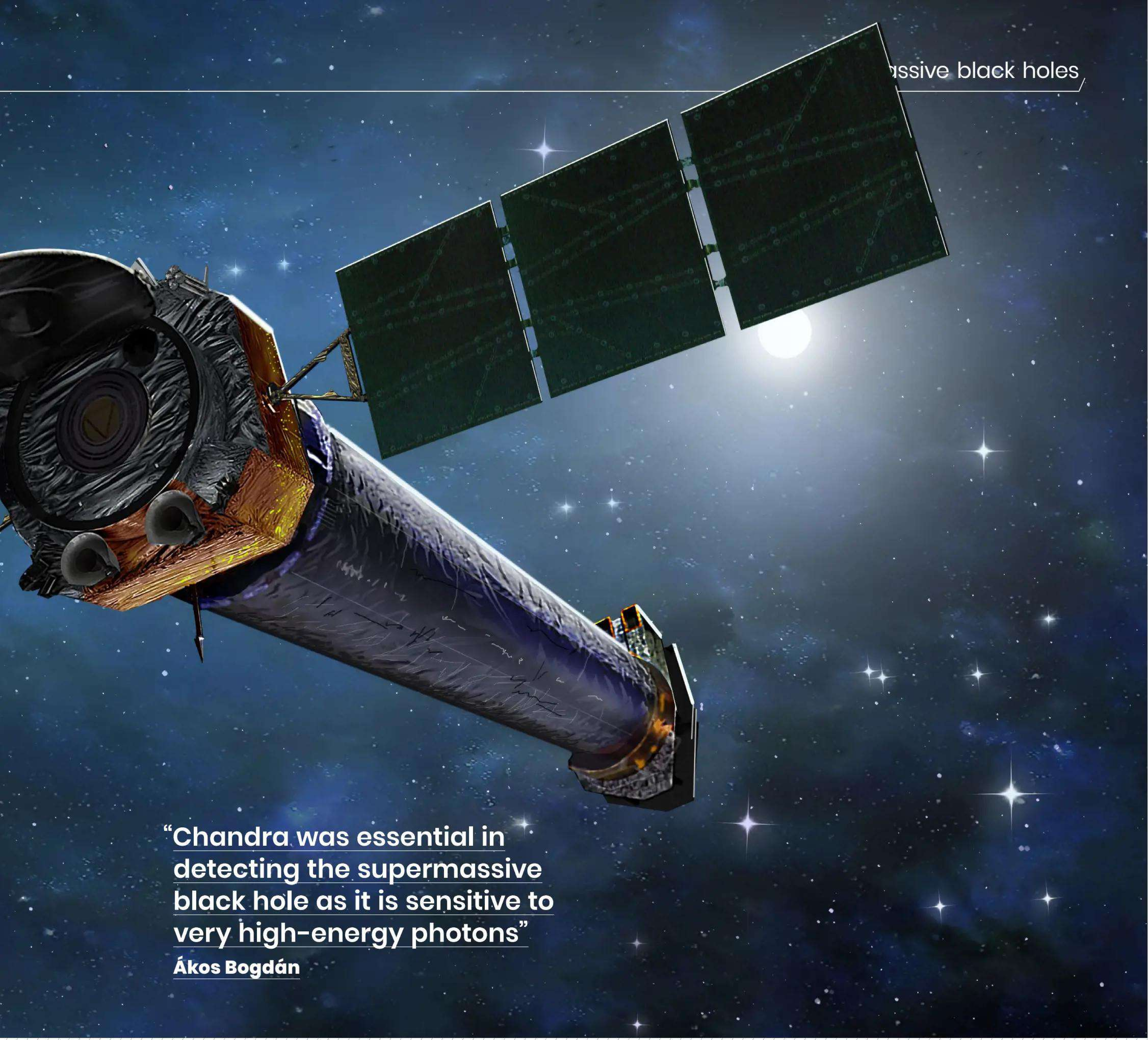
The majority of black holes form when large stars die in supernova explosions, so could this be happening very early on? If so, it would suggest the first stars exploded to create stellar black holes, which then grew through quick mergers with each other.

They've been around for much longer

Maybe the early supermassive black holes were not born after the Big Bang. There's a chance they were from a universe that contracted and recoiled to create the one we're in today. If so, perhaps they are evidence of the Big Bounce theory.

They formed from massive gas cloud collapse

There is now very strong evidence that the supermassive black hole in UHZ1 originated from the collapse of a massive gas cloud. The seed mass of the black hole was about 10,000 to 100,000 times the mass of the Sun.



was suppressed. Large discs of gas could collapse into heavy black hole seeds, she posited, and quickly merge with parent galaxies. So convinced was Natarajan that her theory could be proven, she went as far as predicting that Webb and Chandra would be able to help find these supermassive black holes. Not only that, she said that a high-redshift supermassive black hole could even be behind Abell 2744. As it turned out, she was entirely correct. "UHZ1 is the first candidate that matches all our predicted properties for this transient class of over-massive black hole galaxies," Natarajan says.

Now astronomers think there are many more examples of early supermassive black holes just waiting to be discovered, and you can bet that Webb and Chandra will be used to find them. Goulding says that UHZ1 "may only be the tip of the iceberg," and says Webb has "opened a new window on the early universe". Studying these early supermassive black holes, according to Natarajan, will also show how these objects grow to a point where they can weigh as much as a galaxy's stars, only for the galaxy's growth to outpace it and see the black hole fall behind. "The next major challenge is to detect further supermassive black holes in the early universe," Bogdán says. "Then we can compare the observed and predicted number density of black holes in the early universe, which will provide us with further important insights about the formation scenarios and evolution of the first black holes."

David Crookes
Science and technology journalist
David has been reporting on space, science and technology for many years, has contributed to many books and is a producer for BBC Radio 5 Live.

FOCUS ON

ASTRONOMERS GET CLOSER TO SOLVING THE LINGERING MYSTERY OF FAST RADIO BURSTS

What's more mysterious than explosions happening thousands of times per day all over the sky, with no idea what's causing them?

Reported by Robert Lea

Fast radio bursts (FRBs) are intense, short-lived blasts of radio waves hailing from beyond the Milky Way that can emit the same amount of energy in just thousandths of a second that the Sun takes three days to emit. However, despite their power and the fact that around 10,000 FRBs could erupt in the sky over Earth every day, these blasts of radio waves remain mysterious. One of the biggest puzzles surrounding FRBs is why most flash once and then disappear, while a tiny minority repeat the flash. This has led scientists on a quest to discover the mechanisms that launch FRBs. Some even believe different celestial objects can produce both repeating and non-repeating FRBs.

Scientists from the University of Toronto used the Canadian Hydrogen Intensity Mapping Experiment (CHIME) to focus on the properties of polarised light associated with 128 non-repeating FRBs. This revealed the one-off FRBs seem to originate in faraway galaxies that are much like our own Milky Way, as opposed to the extreme environments that launch their repeating cousins. The results could bring scientists closer to cracking the lingering celestial puzzle of FRBs. The key difference about this research is it really drilled down on the investigation of polarised light. Polarised light is made up of waves that are orientated in the same way – vertically, horizontally or at an angle between those two directions. Changes in polarisation could explain the mechanism that launched the FRB and thus reveal its source. Polarisation can also reveal details about what environments the FRB needed to traverse before reaching our detectors on Earth. This study

represented the first large-scale look at the non-repeating 97 per cent of FRBs in polarised light.

There has been a gap in non-repeating FRB research as it's much easier to observe repeating FRBs since astronomers already know where they're going to occur, meaning it's possible to point any radio telescope at that patch of sky and wait. With non-repeating FRBs, astronomers must have a telescope that can look at a large area of the sky all at once because they don't really know where the signal will come from. "Other studies have looked at the polarisation of maybe ten non-repeating FRBs, but this is the first time where we've looked at more than 100. It allows us to reconsider what we think FRBs are and see how repeating and non-repeating FRBs may be different," said Ayush Pandhi, a PhD student at the University of Toronto.

> "If an FRB passes through more material, it'll rotate more"
> **Ayush Pandhi**

Astronomers wonder whether there is a different phenomenon behind these two types. And Pandhi's team indeed found that non-repeating FRBs seem to be a little different from repeating FRBs, as most of the former seem to come from galaxies like our Milky Way. While the origins of FRBs are shrouded in mystery, these bursts of radio waves can act as messengers of the environments they pass through while racing to Earth. That information is encoded in their polarisation. "If the polarised light passes through electrons and magnetic fields, the angle at which it's polarised rotates, and we can measure that rotation," Pandhi said "If an FRB passes through more material, it'll rotate more. If it passes through less, it'll rotate less."

The fact that the polarisation of non-repeating FRBs is less than that of repeating FRBs indicates the former seems to pass through less material or weaker magnetic fields. Pandhi added that while repeating blasts of radiation seem to be coming from more extreme environments, their non-repeating brethren seem to emerge in slightly less violent environments. One of the big surprises this research delivered was that the polarisation of non-repeating FRBs seems to clear one of the major suspects behind their launch: highly magnetised, rapidly spinning neutron stars, or 'pulsars'.

In terms of figuring out what objects launch FRBs, Pandhi thinks expanding our understanding of the polarisation of these bursts of radio waves could help narrow down theoretical predictions. "It provides another parameter to help us rule out theories about what they could be until we have one that sticks," he said.

The Canadian Hydrogen Intensity Mapping Experiment (CHIME) during construction.

DARK ENERGY

THE MOST DOMINANT FORCE IN THE UNIVERSE IS ALSO ITS MOST MYSTERIOUS AND MOST UNANTICIPATED

Reported by Robert Lea

You have to feel for physicists at the end of the 19th century. After massive advances in physics in the previous 100 years, many thought they had a good handle on the laws of the universe and all that remained for them to do was make more precise measurements. Quickly, the 20th century began to deliver insights that turned this confidence on its head. Arguably, the most shocking of those discoveries came at the end of the century, when it was found that the universe is expanding, and that expansion is accelerating. The force behind this was labelled 'dark energy', but that's just a placeholder. Troublingly, dark energy isn't just an aspect of the cosmos, it's the dominating aspect. And it can't be ignored, as the nature of dark energy could decide what happens at the end of the universe.

Fittingly, scientists are in the dark about what dark energy actually is. Luz Ángela García Peñaloza is a cosmologist at Universidad ECCI in Colombia who has spent the last decade trying to understand it. "It's like looking for a needle in a haystack," she tells **All About Space**. "Except with a needle, you know what it looks like, and you know what it will feel like when it pricks your finger. With dark energy, we don't know what we are looking for. It's a bit hilarious in the sense that we are studying something we just aren't seeing. But understanding dark energy will help us understand so many fundamental questions."

Even before dark energy was found in the cosmic recipe of the universe, the 1900s had been delivering findings denting scientists' confidence. Quantum physics emerged, showing the rules of the subatomic were not just different from those of the macroscopic everyday world, but were counterintuitive and disturbing, challenging the notion of what's real. Einstein revealed space and time could unite as a single four-dimensional entity called 'space-time', set the speed limit of the cosmos to the speed of light and then showed in 1915 that gravity wasn't as Newton imagined, but emerges from the very curvature of space-time.

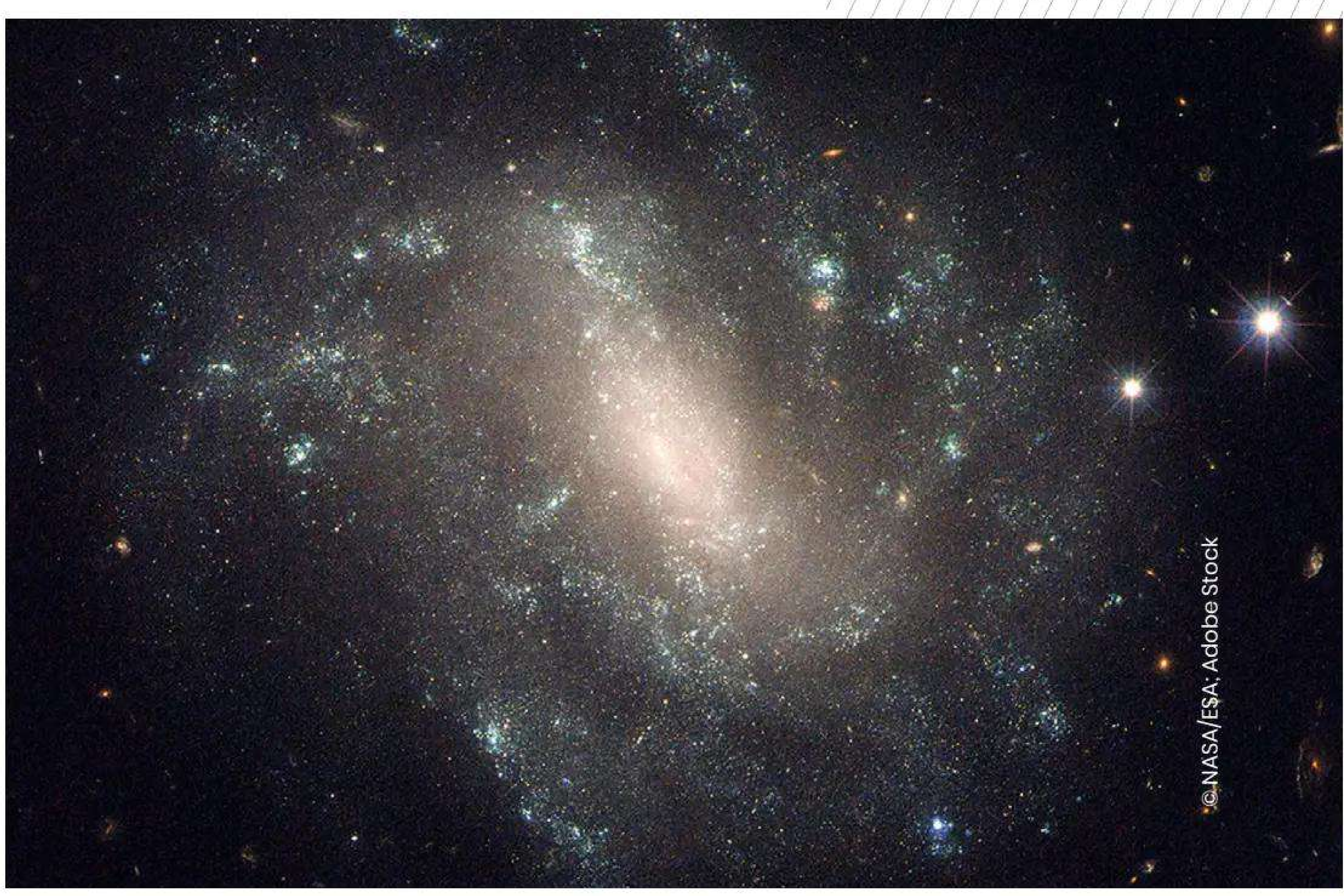
Hints at the expansion of the universe began when using this latter theory, general relativity, and its equations to formulate an equation to describe the state of the cosmos. Einstein found that it predicted that the universe wouldn't 'hold still'. The consensus at the time was that the universe was static, neither expanding nor contracting, and Einstein agreed with this. But general relativity predicted a dynamic universe. To combat this, Einstein introduced a 'fudge factor' to his work to counteract gravity. This was known as the cosmological constant, represented by the Greek letter lambda. The cosmological constant would become a headache for physicists for decades, albeit in a different form, but we'll get to that.

Einstein would rue the introduction of the cosmological constant when Edwin Hubble made observations of distant galaxies that showed they were receding away from each other, and from us. This showed that the universe isn't in a steady state, but is expanding. In light of this evidence, Einstein dropped the cosmological constant, later describing it as his greatest blunder. But the cosmological constant wouldn't stay in the theoretical dustbin for long, thanks to a massive revelation at the end of the 20th century.

If physicists thought they were getting out of the 1900s with a good understanding of the universe and a few 'known unknowns' left to be explained in the new millennium, they were in for a massive shock. This revolutionary century had one last major twist to deliver, and this twist would foreshadow the major direction of cosmology in the 2000s. In 1998, two independent teams of astronomers presented evidence that not only is the universe expanding, but this expansion is also accelerating. This evidence was delivered in the form of observations of distant cosmic explosions called type Ia supernovae, which astronomers call 'standard candles' because their light output is so uniform they can be used to measure cosmic distances. This revealed an almost anti-gravitational force working on incredibly large scales between galaxies and clusters of galaxies, forcing them apart by stretching the very fabric of space-time. This came to be known as dark energy.

"This discovery was completely unexpected," García Peñaloza says. "It was completely beyond the imagination of cosmologists working in the field 26 years ago." That meant dark energy had to be

In 2016, Hubble observations showed the universe was expanding faster than predicted



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THE DIFFERENT KINDS OF DARK ENERGY

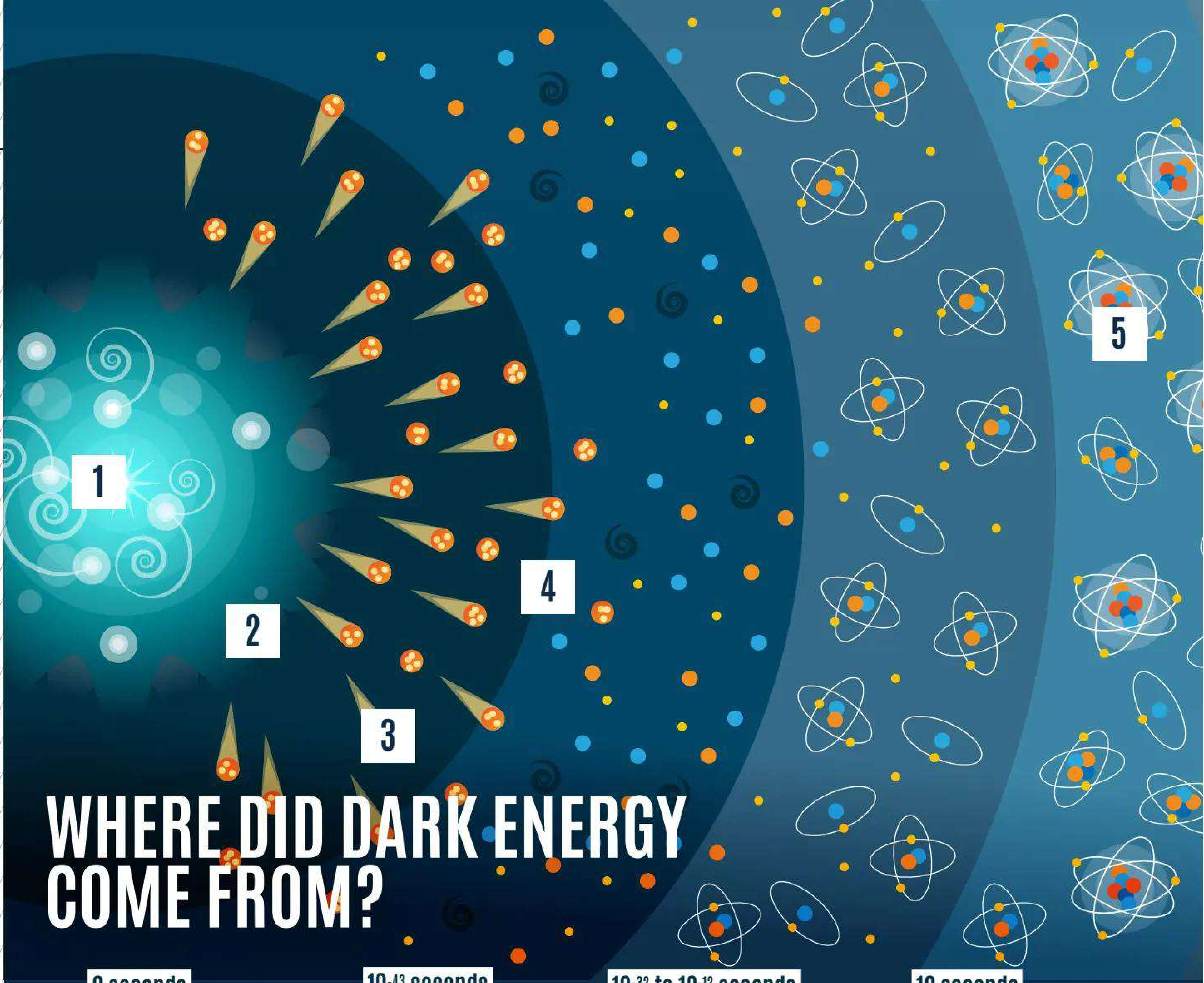
The cosmological constant and vacuum energy
The leading candidate for dark energy represents vacuum energy arising from 'virtual particles' popping in and out of existence in empty space. The main problem with this candidate is the massive difference between its theoretical value and its observed value.

The universal quantum field
Researchers struggle to unite cosmology with quantum physics. Another candidate for dark energy arises from quantum mechanics. This suggests that a scalar field permeates the entire universe, replicating the acceleration effects of the cosmological constant.

The fifth force of nature
Should a dark energy universal scalar field exist, it could represent a fifth force of nature, joining its counterpart gravity, electromagnetism and the strong and weak nuclear forces. This quintessence would differ from the cosmological constant by varying in time.

Tachyonic fields, phantom energy and more
Dark energy is a complete mystery, so theoretical physicists are only limited by their imaginations when suggesting candidates. That has resulted in a raft of plausible candidates such as tachyons – hypothetical particles which are travelling faster than light and backwards in time.

Modified theories of gravity
While it's an idea that has fallen out of favour, scientists haven't completely ruled out the idea that the observed effects of dark energy and dark matter are explained by revised theories of gravity, and thus don't exist at all.



WHERE DID DARK ENERGY COME FROM?

0 seconds

1 Before the beginning
All the matter and energy in the universe existed within a single infinitesimal point, a gravitational singularity a billionth the size of a proton. Possibly due to a quantum fluctuation, a period of rapid expansion began.

10^{-43} seconds

2 Grand unification
The universe was still at an infinitesimal size. At these incredible energy levels, the universe's four fundamental forces were unified. Gravity soon separated to act independently, followed by electromagnetism.

10^{-32} to 10^{-12} seconds

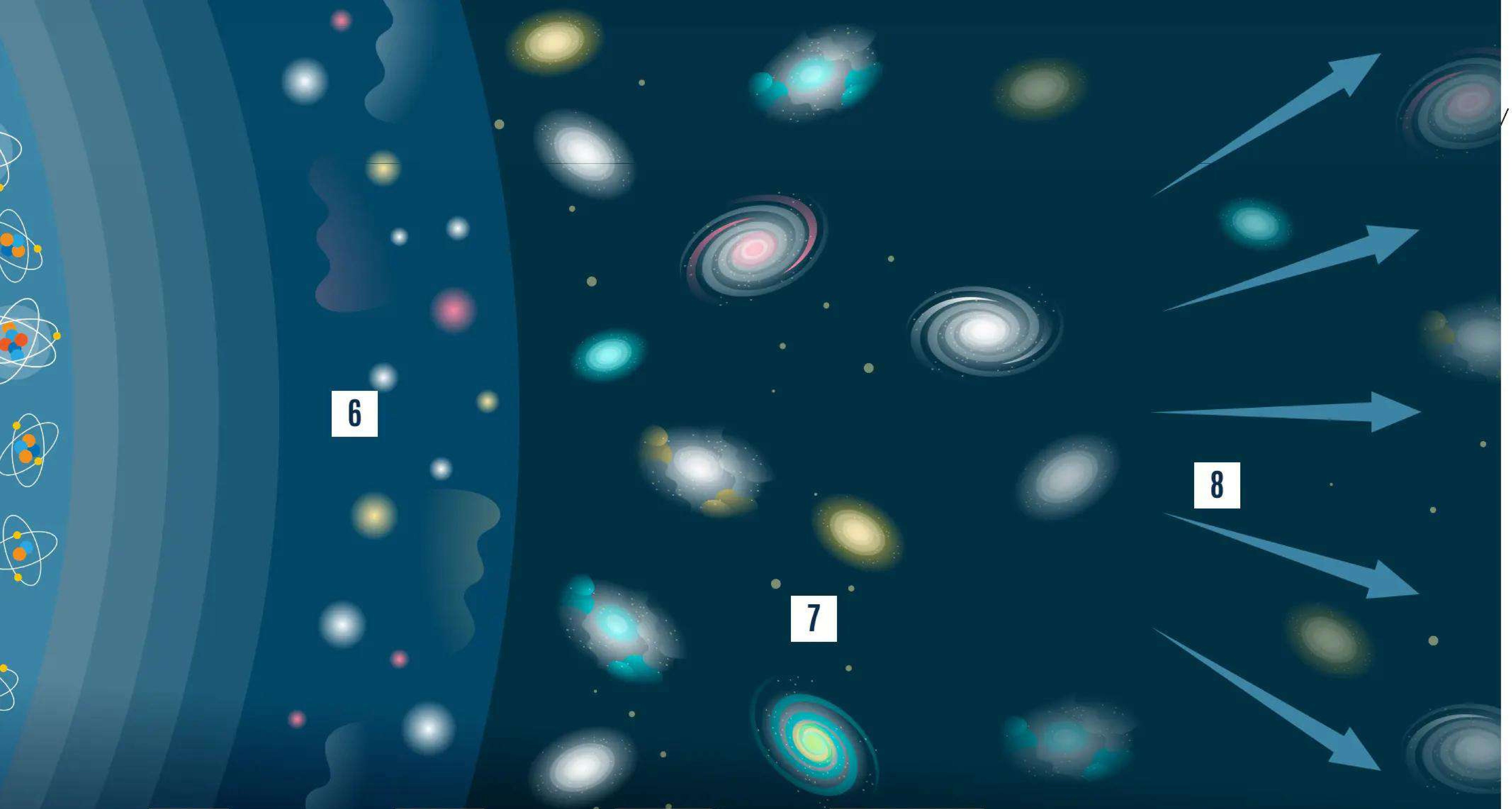
3 The quark epoch
As the universe began to expand, its 'supercooled' elementary particles formed as a 'hot soup' of ionised plasma. Matter particles interacted with the Higgs field, thus acquiring mass. The four fundamental forces were separated.

10 seconds

4 No more positrons
Positrons and electrons annihilated each other, with a small imbalance favouring electrons. These impeded the travelling of photons, meaning the universe was opaque to light.

explained by something completely outside of our best understanding of physics at that time." One of the most extraordinary things about dark energy is how dominant it is in the universe. Since the discovery of the accelerated expansion of the universe, using data from the European Space Agency's (ESA) Planck spacecraft, scientists have found that of the total energy and mass in the universe, 68 per cent is dark energy and 26 per cent is dark matter, which we also don't understand. That means every star, planet, moon, asteroid, comet, cosmic dust cloud, neutron star, black hole, white dwarf, human, coffee mug and cat – everything we understand, in other words – accounts for just five per cent of the energy and mass in the universe.

But dark energy wasn't always the ruling force it is today in the so-called 'dark energy-dominated epoch' of the universe. There are two distinct eras of cosmic expansion, and the dark energy-driven era is the latest. The first period of rapid expansion began with the event at the beginning of time we know as the Big Bang. Dark energy and the accelerating expansion it powers may well be dominant now, but this is blown out of the water by this initial period of expansion. In our current dark energy-dominated epoch, the further away a galaxy is, the faster it's receding. Currently, scientists estimate that galaxies are getting 0.007 per cent further away from each other every million years. A galaxy 100 million light years away is receding at 2,150 kilometres (1,336 miles) per second, and a galaxy a billion light years away is receding ten times faster at around 21,500 kilometres (13,360 miles) per second.



47,000 to 370,000 years

5 The first light

The gravitational collapse of matter formed structure and atoms began to form. As free electrons were snatched up, light was free to travel. The universe became transparent.

100 to 300 million years

6 The first stars

Ordinary matter particles fell into structures created by dark matter. The stars began to take shape, and the first stars began to shine. Expansion slowed considerably.

380 million to 1 billion years

7 Quasars, galaxies and black holes

The first quasars and galaxies were born. The oldest known galaxy with a supermassive black hole existed at 770 million years, hinting that black holes started to grow much earlier than this.

8.8 billion years to 9.8 billion years

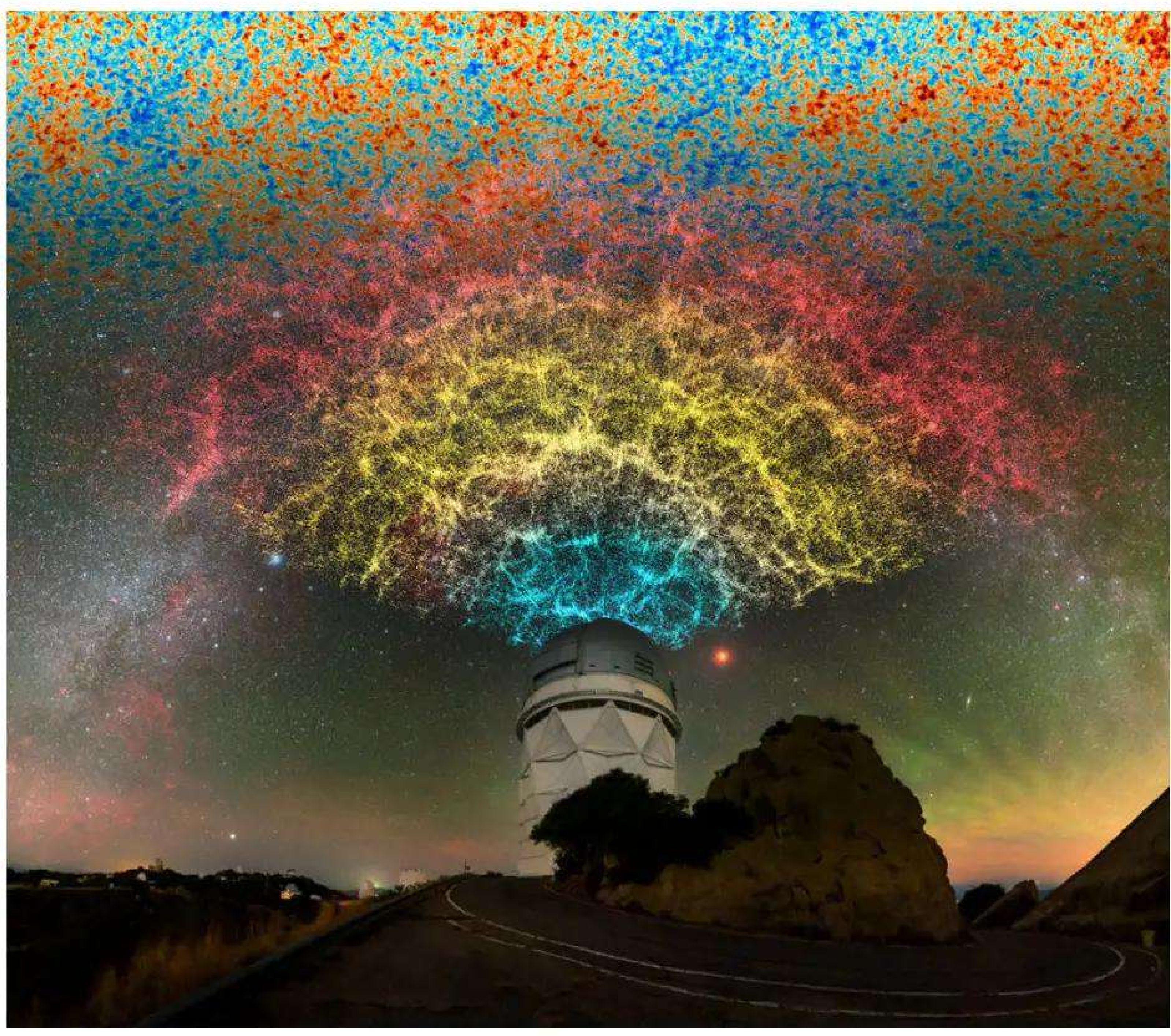
8 Dark energy dominates

Matter lost its dominance over the universe. The dark energy-dominated epoch began, accelerating expansion.

> "It was beyond the imagination of cosmologists working in the field 26 years ago"
>
> **Luz Ángela García Peñaloza**

GN-z11 is one of the oldest galaxies ever discovered. We see it as it was when the universe was just 400 million years old. That means it's also one of the most distant galaxies, at an estimated 32 billion light years away. Dark energy is expanding the fabric of space at such a rate that GN-z11 is moving away from us at an estimated speed of 687,000 kilometres (426,882 miles) per second. That's over twice the speed of light, which may seem impossible given the speed limit for the cosmos is the speed of light in a vacuum – but there's a loophole. That cosmic speed limit applies to things with mass moving through space and time, not to the fabric of space-time itself.

As mind-bogglingly fast as the current expansion is, the Big Bang-triggered period of expansion blows it away. This initial inflationary epoch saw the volume of the cosmos increase by a factor of 10^{26}. To picture that, imagine your fingernail going from growing at one nanometre per second to suddenly growing by 10.6 light years in a second. That's about 32 million times



The Dark Energy Spectroscopic Instrument (DESI) scans the universe over one-third of the night sky

THE END OF THE UNIVERSE

How the universe ends depends on who wins in a cosmic tug of war

Big Freeze

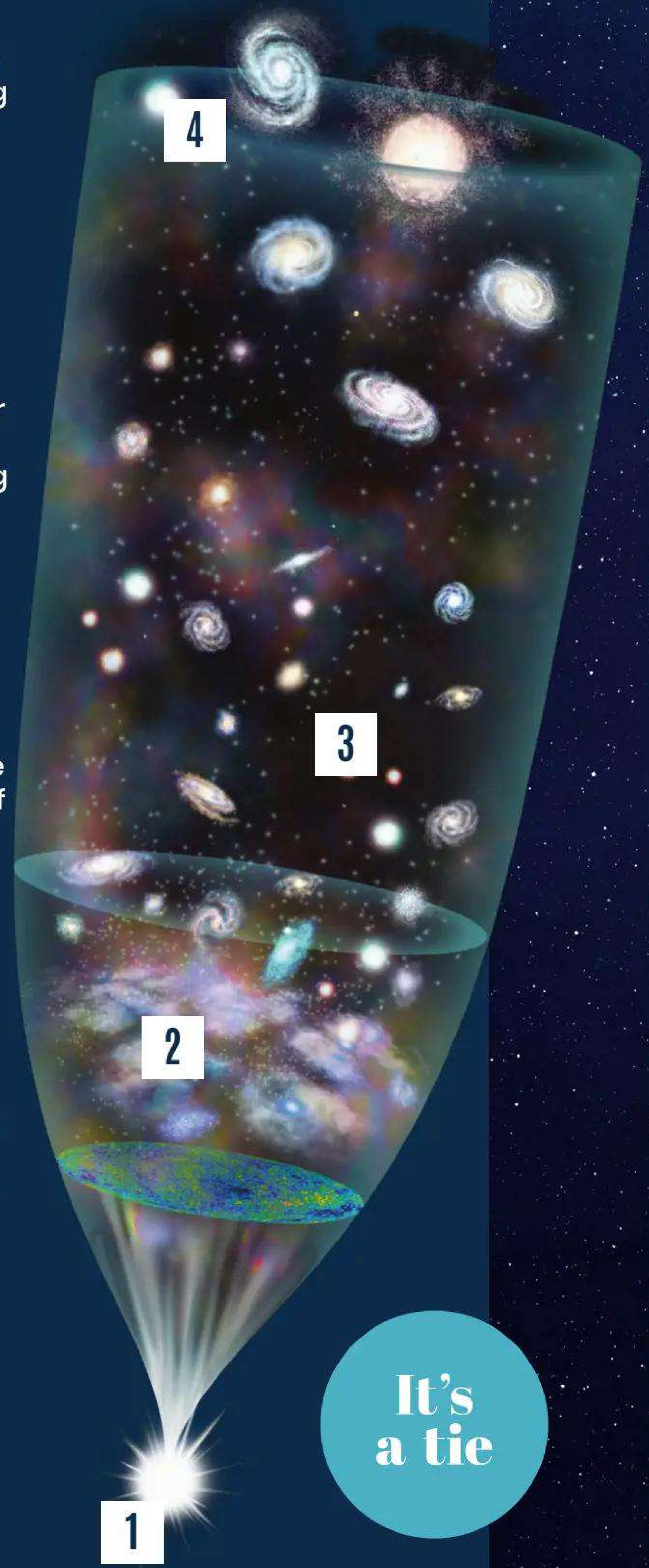
Rather than rip apart, there's a theory that the universe will continue to expand and then simply stop. Dark energy will push the universe apart, with the energy inside it becoming more and more spread out until it reaches a balancing point with dark matter. New stars will be unable to form because the supplies of gas are too thin, and there will be a uniform temperature. It will result in the Big Freeze, leaving the universe dead and empty.

1 The beginning
As with all these theories, everything starts with the Big Bang, which happened 13.8 billion years ago.

2 Period of expansion
The universe has been expanding for billions of years. It began accelerating 6 billion years ago and heat is being dispersed.

3 Continuing to expand
As the universe expands, the space between clusters of galaxies will grow. The gases needed for star formation will run thin.

4 The Big Freeze
The universe cools and heat death results: stars die and matter decays since there is no temperature difference to allow energy to be consumed.



It's a tie

Big Crunch

For the 'Big Crunch' to occur, gravity would slow expansion and drag objects back, collapsing the universe in on itself. There would need to be enough matter with a density greater than critical density to exert the required gravitational force. It would also mean dark matter dominating over dark energy. The result would be the creation of the largest ever black hole – or the ignition of another, reforming Big Bang.

1 Universe expands
The universe is currently expanding and will continue to do so for many more billions of years.

2 Reaching a maximum
The Big Crunch theory supposes space is a positive constant curvature, or a closed universe. If so, a maximum expansion is reached.

3 Greater density
The density of the universe is greater than the critical value. Gravity is increased and starts to contract the universe.

4 Black hole
As galaxy clusters are pulled closer and merge, stars explode and black holes emerge as the universe collapses under its own gravity.

5 A state of singularity
The black holes coalesce and a unified black hole is created. A very hot point is reached.

6 Start again
The singularity is incredibly dense, and in theory could spark another Big Bang, starting the whole cycle again.

Dark matter wins

Big Rip

It was once widely thought that the gravitational pull of the universe would cause its expansion to slow down, but evidence points instead to acceleration. Indeed, the gravitational attraction of dark matter began to weaken 8 billion years after the Big Bang, putting dark energy in a dominant position. This appears to be pushing the universe apart, and if it continues to speed up, the constituents of matter could start to separate, causing the Big Rip.

1 The Big Bang Dark matter and dark energy are said to have originated at the point of the Big Bang, following which atoms were formed.

2 Dark matter Dark matter exceeded the density of dark energy for billions of years. It made up about 63 per cent of the universe when it was just a few hundred thousand years old.

3 Dark energy Around 6 billion years ago, the density of dark energy exceeded the density of dark matter for the first time.

4 Galaxy formation The merging and clumping of dark matter formed galaxies, which started small and drew in other objects to become larger.

5 Accelerating expansion Gravity decreased due to the falling density of dark matter. Dark energy began to accelerate the universe's expansion.

6 Faster and faster Should gravity be thwarted in its attempts to make the universe collapse again, expansion would accelerate further.

7 Torn apart Eventually everything from galaxies to the planets, stars and subatomic particles would be ripped apart.

the speed of light. "If this was the kind of expansion we were experiencing now, you would look up to the night sky and see stars, and the next instant they would completely disappear," García Peñaloza explains.

At the time of Big Bang-driven inflation, the universe was dominated by energy, and this period is known as the radiation-dominated epoch. This came to an end as the first atoms formed the first stars and galaxies, signalling the universe's second major epoch, the matter-dominated era. During the matter-dominated era of the universe, the expansion of the cosmos slowed to a crawl and then a near-stop, as you would expect from anything given one sudden push. That was until around 4 to 5 billion years ago, when the universe was under 10 billion years old. At this point, dark energy suddenly took over and began expanding the universe again, but faster and faster. The universe had entered the dark energy-dominated epoch, its third major period, which it's still in today.

To picture why this is so troubling to scientists, imagine taking a simple toy car and giving it one push so it races across your dining table. The car moves rapidly at first and gradually slows down. That's like the radiation and matter-dominated eras of the cosmos. Just as you see the car about to stop, it suddenly starts speeding up without you touching it again, and the toy keeps accelerating. That's akin to the dark energy-dominated era of the universe. You'd want to know what gave that toy car the additional sustained push, and scientists are desperate to know what is doing the same for the expansion of the universe.

There are several theories about what dark energy is, but the leading suspect has a name you'll find familiar. To represent the action of dark energy, scientists resurrected the concept of the cosmological constant, once again denoted by lambda. This time it isn't just balancing gravity – lambda is acting against it. The leading candidate for the cosmological constant is the so-called vacuum energy of 'empty' space. The uncertainty principle tells us that the smaller a space we define, the less sure we can be of the energy within that space, so there's no such thing as empty space. Because energy can never be exactly zero in any region, particles called 'virtual particles' can briefly pop into existence. This is as long as they're created as two particles, as that means the net energy is still zero – one matter and the other antimatter, with equal and opposite charges. Those particles rapidly meet and annihilate each other, returning their energy to space.

An illustration of what the universe may have looked like during its initial era of inflation

Supernovae helped scientists discover the acceleration of universal expansion

In a way, it's almost as if space itself has an overdraft facility. The result of these particles popping in and out of existence is 'vacuum energy', currently the best explanation we have for the cosmological constant, and thus dark energy. There's a hitch, however. Virtual particles are the remit of quantum physics, and more precisely quantum field theory (QFT). Indeed, QFT predicts a value for lambda and for the Hubble constant, the speed at which the universe is expanding. Also, observations of type Ia supernovae give astronomers a value of lambda, and for the Hubble constant too.

The value of lambda predicted by QFT is vastly larger than the observable value – by as much as 10^{21} greater than the observed value. It's for good reason the cosmological constant has been called the worst prediction in the history of physics by some exasperated scientists. To give you an idea of the scale of this disagreement, if you made a measurement of a human hair and determined it to be 0.05 millimetres wide, and someone else measured it and said it was 5.3 light years wide, that would be a disparity of 10^{21}, making that a better prediction of human hair width than predictions of the cosmological constant by 100 orders of magnitude.

As astronomy tools improve and we get a picture of the early universe, cosmologists are starting to make progress in deciphering dark energy. We don't yet know what this cosmic needle in a universal haystack looks or feels like, but we are getting to the point at which we can start to figure out what it doesn't look or feel like. "We're in the era of cosmological precision. It's interesting because we're getting to the point that we can not only rule out some models, but also start distinguishing things about dark energy," García Peñaloza says. "We're starting to discriminate between the effects of different models. And that was something that we couldn't do ten years ago."

This is a problem that physicists can't be complacent about. Just like the force acting on our toy car will depend on whether it remains on the table or plunges over the edge, the final fate of the universe rests on what recipe of dark energy is the right one. Before 1998 and the discovery of dark energy, scientists assumed that the universe would end in a 'Big Crunch', with gravity becoming the dominant factor and drawing all the matter together, recreating a hot, dense state in almost a rewound Big Bang. Dark energy challenged that, but a similar ending to the 'Big Crunch' may not be off

the table. "The end of the universe depends on the amount of dark energy and the way it's acting on the universe," García Peñaloza says. "If dark energy is weakening we will see a decrease in the acceleration rate, and the universe could end up drawing together in something like a 'Big Crunch'."

Meanwhile, it's possible that dark energy reaches a plateau and space continues to stretch forever, leading to a cold, dark demise, going out with a whimper, not a bang. Alternatively, if dark energy continues to strengthen, it's possible a 'Big Rip' scenario could occur. This would see the increasing force of dark energy cause a sudden break in the fabric of space-time. "Let's assume dark energy is actually increasing its effect," García Peñaloza says. "In that case, it means eventually, after aeons, the galaxies in the night sky will diminish until the point we'll have a very dark night because galaxies are just too far away from us to observe."

This reveals that dark energy is telling us something important and quite profound about the period of the universe in which humanity finds itself. In billions of years, the distant galaxies will have expanded so far away from the galactic homes of whatever intelligent life exists in the cosmos that when they look to the skies, they will see a dark void bereft of light. As García Peñaloza points out, this doesn't indicate some special privilege afforded to humanity. "It's a cool coincidence," she says. "I wouldn't go further than that. It's a really cool one, though, just because we could have missed this stage of the universe."

It's more likely that the time it takes stars and planets to form with the right stuff and then intelligent life to develop on those worlds is similar to the current age of the cosmos. One in which the heavens are available to us. It does make you realise that we live at a special and lucky time in the cosmos in which we are afforded the ability to study its wonders and mysteries. Thankfully, dark energy hasn't completely left us in the dark just yet.

Robert Lea
Space science writer
Rob is a science writer with a degree in physics and astronomy. He specialises in physics, astronomy, astrophysics and quantum physics.

HOW DARK ENERGY BEHAVES

1 The cosmic tug of war
In many ways, dark energy can be considered the 'evil' counterpart of gravity. Gravity's influence draws matter in the galaxy together; dark energy works to push it apart.

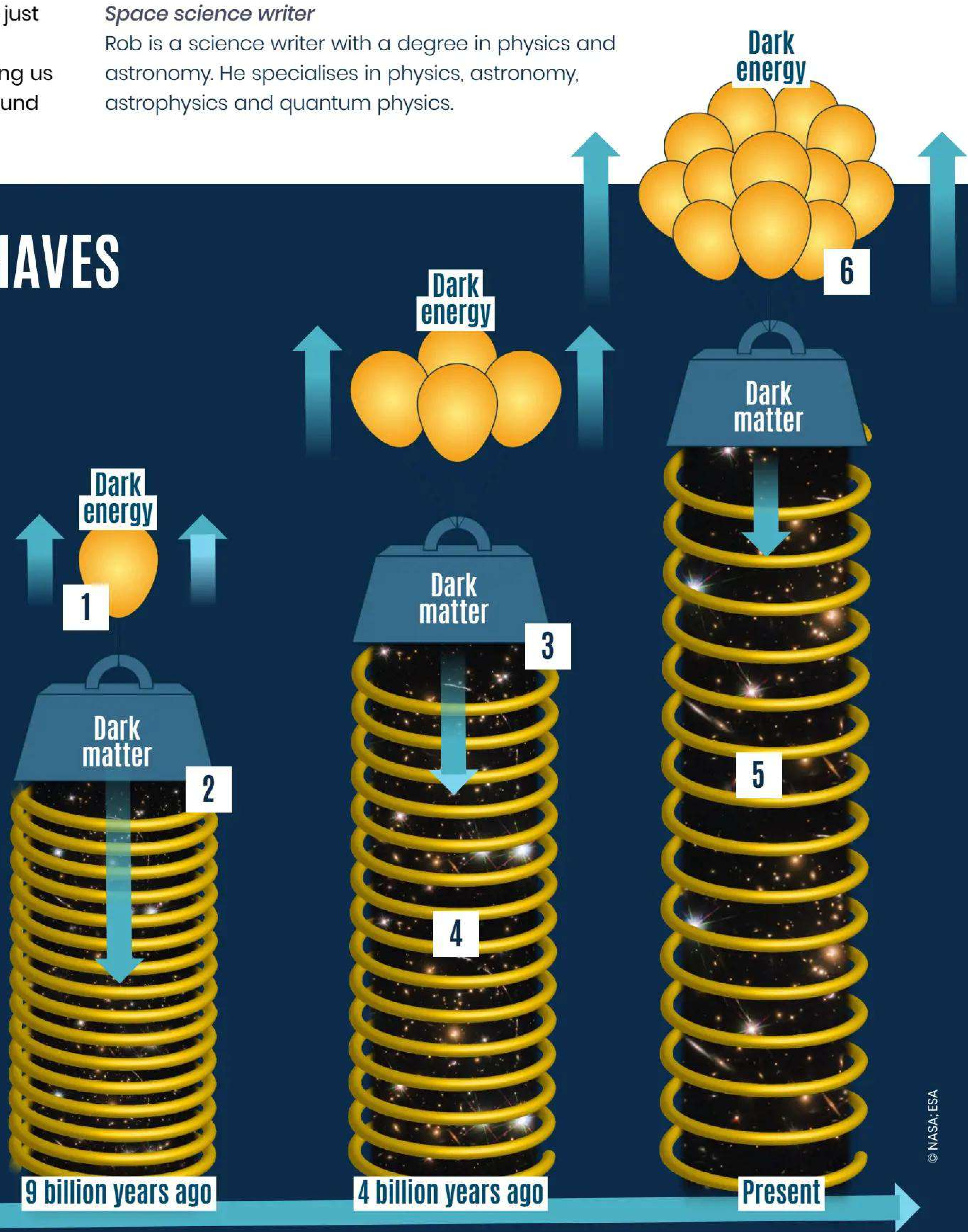
2 Holding it together
Astronomers calculated that the gravitational influence of visible matter wasn't enough to hold galaxies together.

3 Dark matter boosts gravity
There's an unseen form of matter exerting its influence. Dark matter accounts for about 80 per cent of the matter in the universe.

4 The dark universe at war
As dark matter outweighs ordinary matter, it's dark matter's gravitational influence that dark energy is working against.

5 The space between us
Dark energy seems to expand the very space between galaxies rather than the galaxies themselves.

6 Where will it all end?
The universe could succumb to either one of these influences, stretching out to an inevitable 'heat death' or snapping back and contracting.



SPACE SCIENCE

Telescopes and space missions help us better understand the cosmos


"The idea of the speed of light as an ultimate cosmic speed limit only emerged through Einstein's special theory of relativity"
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MISSION TO MARS

It will be a bigger leap than the Moon landing of 1969, but when will humans actually land on the Red Planet?

Reported by David Crookes

Sending astronauts to the surface of the Moon for the first time in more than 50 years remains one of NASA's key ambitions. The space agency hopes a crew of four will land close to the lunar south pole in 2026, a year after another crew is sent around the Moon and back. The idea is that they'll set up a mini-greenhouse, conduct experiments and discover more about Earth's natural satellite. It's exciting for sure, taking humans beyond the International Space Station and heralding a new era in space exploration. But are there plans to allow crews to travel even further? There certainly are. NASA and other space agencies also have Mars in their sights, and if the plans ever get off the ground, they'll put people on or close to the Red Planet for the very first time.

5 REASONS WE NEED TO GO TO MARS

Why getting humankind to the Red Planet is so important

1 Testing technologies for space exploration

A manned mission to the Red Planet will involve state-of-the-art technology, but Mars also offers the opportunity to test our new spacecraft and instruments to the extreme. While we haven't landed any humans on Martian soil as of yet, every mission that we have and will continue to send in the future will yield important information from their surroundings. This data will serve as a stepping stone, paving the way for human exploration and the technology to get us to Mars.

2 Establishing human life elsewhere

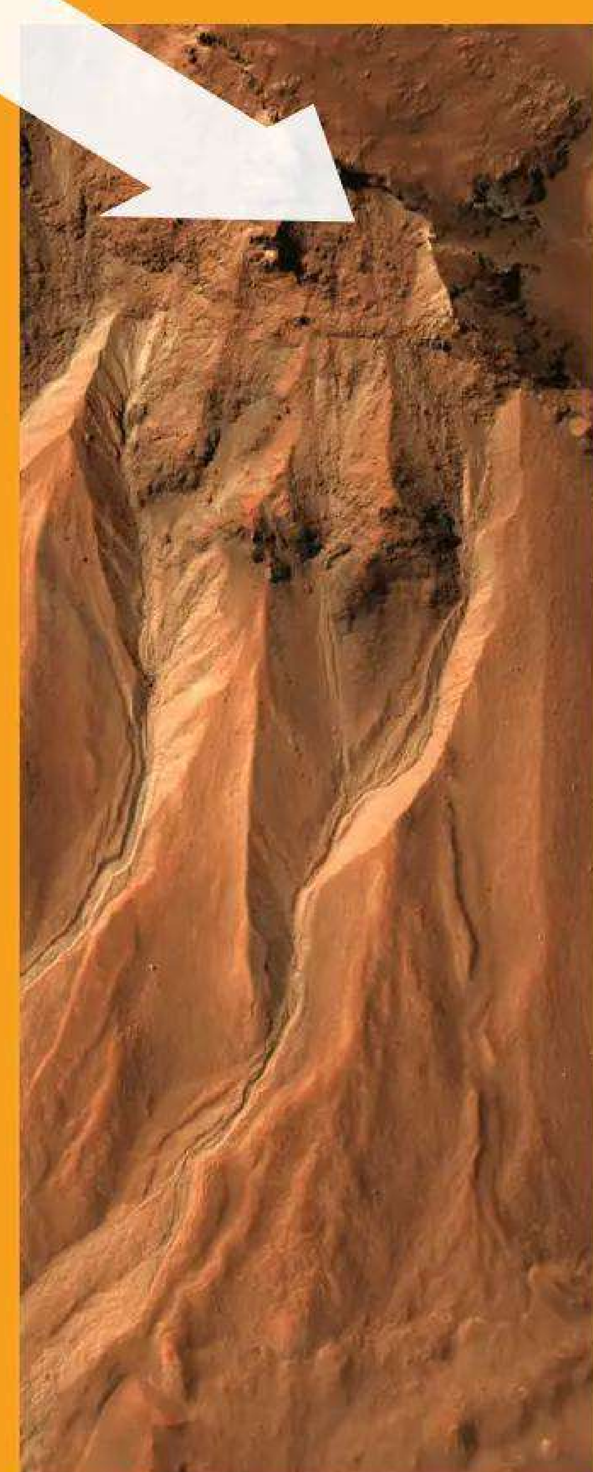
At the moment, the only planet we know of that harbours complex life is Earth. But what if we humans could exist elsewhere? Mars has the potential to offer colonisation as an option, despite its hostile environment.

3 Conquering frontiers

Despite being the closest planet bearing some similarities to Earth, experts haven't let the fact that a manned mission to Mars would be difficult escape their notice. However, we have the knowledge and technology to make the journey to another planet possible. Making the journey to Mars and landing on its surface would indeed be the challenge of a lifetime.

4 Looking for life

A common misconception is that for a planet to be habitable, it must have exactly the same characteristics as Earth. A frozen planet harbouring a single organism surviving comfortably under an icy planetary crust still means the world is habitable, no matter the differences compared to our home. While Mars cannot support humans without the aid of technology, it can provide clues on the conditions for life both under its surface and on other planets in the universe.



5 Understanding Mars' past and present to look into the future

Expanding our knowledge about Mars is very important, especially if we hope to set foot on the Red Planet sometime in the future. Learning from past and current missions has broadened our horizons immeasurably, giving us the confidence to start thinking about what to expect when the first crew touches down on the ruddy soil. We've discovered that Mars may have supported life in its past – according to the damp soil that Curiosity found recently. Of course, rovers aren't as dextrous as humans, which means they have several limitations when it comes to looking for clues. This is another reason why we need to go to Mars.

GETTING TO MARS

How we're preparing for manned missions

1 Practising on the ISS

Long-duration stays aboard the ISS are helping prepare crews for Mars. These stays normally last around six months.

2 SLS rocket

NASA's Space Launch System will enable humans to explore destinations beyond the Moon.

3 Crew capsule

The Orion spacecraft is NASA's answer to launching astronauts from Earth and returning them from Mars.

4 Deep-space habitats

Getting to Mars will take up to nine months, so astronauts will need something larger than a small shuttle to live in.

5 Ion engines

The spacecraft that takes humans to Mars will likely use some form of solar electric propulsion, or ion engines, to gradually accelerate and decelerate the spacecraft.

6 Snagging an asteroid

A chunk of asteroid could be redirected into lunar orbit. Astronauts would be sent to explore it and practise techniques they would need on Mars missions.

7 Robotic helpers

Images from orbiters and data from rovers at Mars will be used to pick a landing site for the manned missions, with a number of candidates already being discussed.

"Funding and time are certainly of the essence"

A FLYBY OF MARS

What would happen during a 2033 flyby of the Red Planet?

1 All aboard

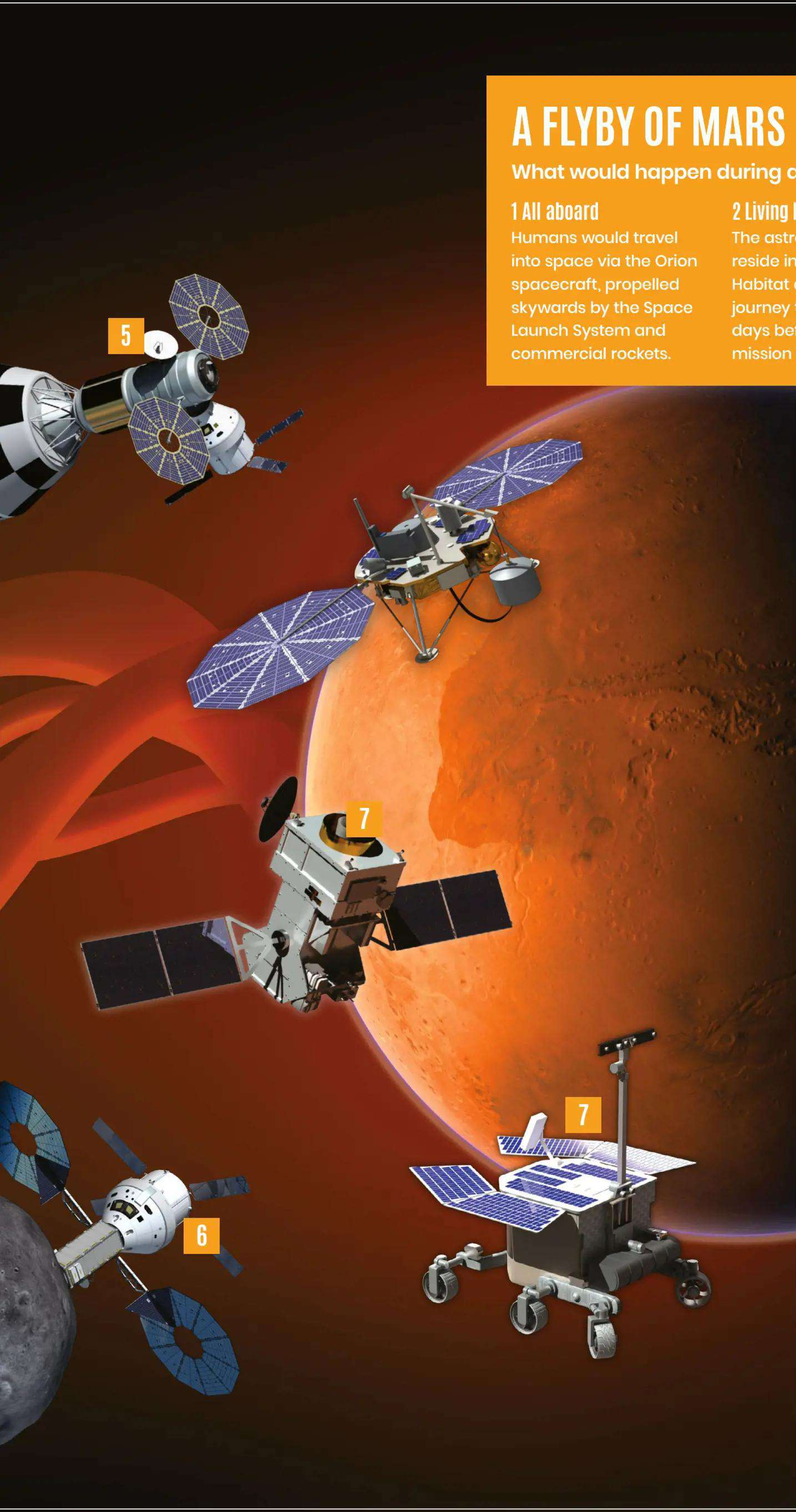
Humans would travel into space via the Orion spacecraft, propelled skywards by the Space Launch System and commercial rockets.

2 Living life

The astronauts would reside in the Mars Transit Habitat and embark on a journey taking some 200 days before entering the mission vehicle.

3 Destination

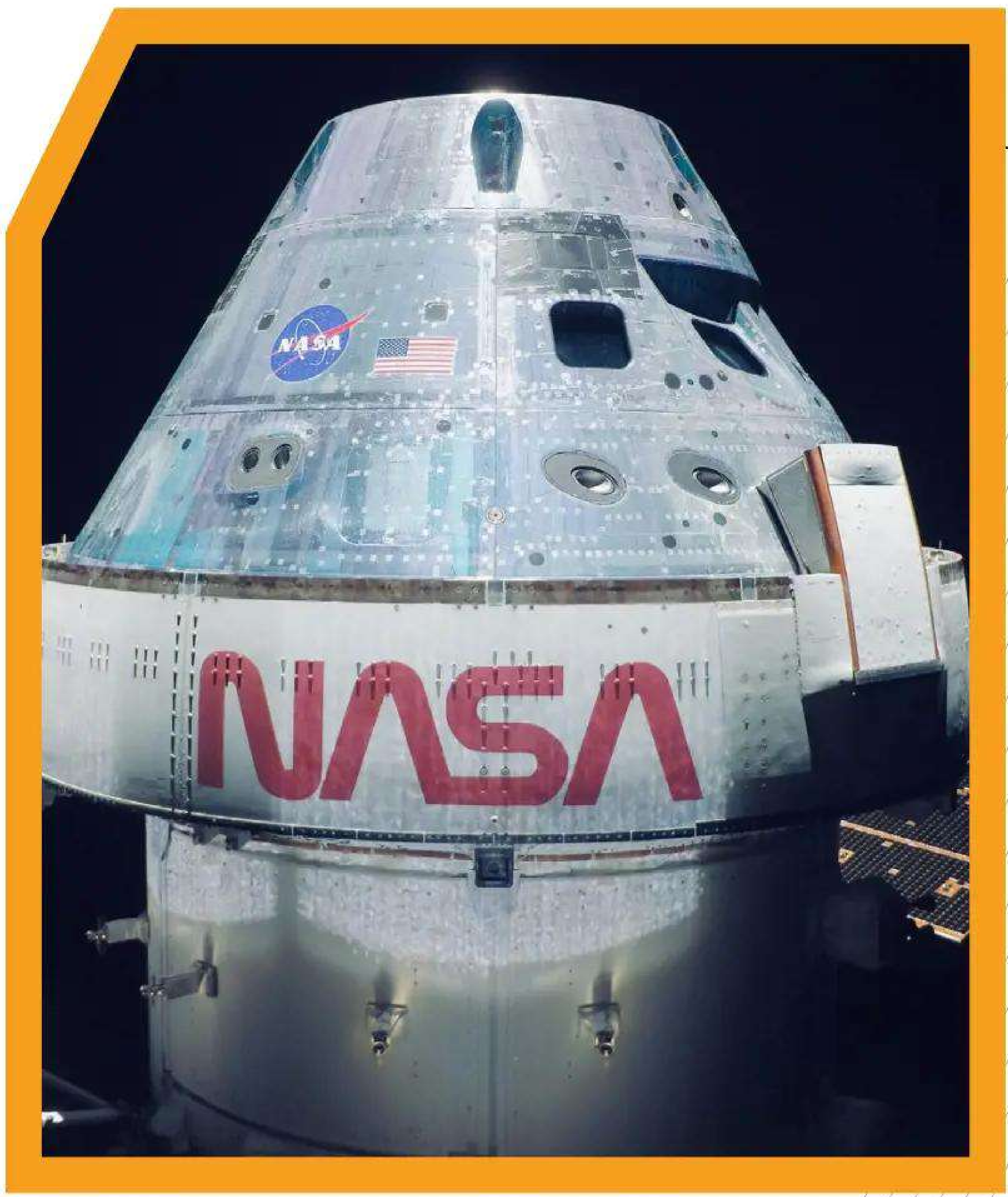
The crew would spend 30 days in a high Mars orbit. When they're finished, they'll return to Earth via a Venus flyby and gravity assist.



Plans to go to Mars aren't new. In 1998, a nonprofit called Mars Society was created with the aim of making human missions to the planet a priority. In 2003, NASA launched the rovers Spirit and Opportunity to explore the Martian landscape, and in 2004 it discussed a desire to send crews to Mars, citing 2020 as the latest year for such a human expedition. Although a host of robots have been revealing many of Mars' secrets, such endeavours have not been without their problems, particularly of late. The Mars Sample Return (MSR) mission, for example, aims to use a robot to retrieve samples gathered by Perseverance, but the budget is vastly exceeding initial predictions and the schedule is slipping beyond the initial return year of 2033.

The good news is that such plans would help pave the way for future crewed missions if they come to fruition. "The Mars Sample Return mission, when completed, should provide much needed data on the underground composition of Martian soil, including ancient or even current biological activity on the planet," says Dr Stamatios M. Krimigis, emeritus head of the Space Exploration Sector of Johns Hopkins University's Applied Physics Laboratory.

Even if MSR doesn't succeed, astronomers are gathering data and making headway in other ways. The Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE), for instance, has been able to use solid-oxide electrolysis to produce oxygen from carbon monoxide in the Martian atmosphere. "It's been 100 per cent successful and totally encouraging," says Dr Michael Hecht, associate director for research management at the Massachusetts Institute of Technology's Haystack Observatory. The technology behind MOXIE, if scaled up, could provide breathable oxygen, oxidiser and propellant on Mars, and could also produce water. "But as with anything we send to Mars, a lot of engineering work remains before we



have a workable full-scale flight system," Hecht tells **All About Space**. "The goal of MOXIE was to retire the unusual level of risk associated with this very new technology, and we've done that."

Another major program in NASA's plans for Mars is the Crew Health and Performance Exploration Analog (CHAPEA) mission, the first part of which has been well underway. A 3D-printed habitat called the Mars Dune Alpha has been developed at Johnson Space Center in Houston to simulate the challenges of a mission on Mars. A four-person crew – Nathan Jones, Kelly Haston, Anca Selariu and Ross Brockwell – has been living and working inside the habitat for a year-long mission. During that time, they've been growing and harvesting crops including peppers, tomatoes and leafy greens; embarked on Mars walks in conditions that mirror those on the Red Planet and conducted biological and physical science investigations. They've also been faced with urgent challenges such as equipment failure and communication delays. The aim is to test the health and performance of potential crews sent to Mars, and it's proven sufficiently useful that another four-person crew is being recruited for the second of three experiments. Those with a master's degree in a STEM field or a minimum of 1,000 hours piloting an aircraft have been submitting their applications. So long as they're aged between 30 and 55 and in good health, they're in with a shot.

Even so, it's one thing to experiment on the ground and quite another to send

The Orion spacecraft will be used in the Moon to Mars initiative, with the SLS being the primary launch vehicle

ON THE SURFACE OF MARS

1 Better than robots
What rovers have accomplished in their years on Mars could have been done by a team of astronauts in just weeks.

2 No oxygen
Mars' atmosphere is a very thin envelope of mostly carbon dioxide gas and isn't breathable. The first colonists will only be able to go out in spacesuits, but after hundreds or maybe thousands of years, it might be possible to terraform the Red Planet to be more like Earth.

3 Frosty nights
Temperatures on Mars plummet as low as -153 degrees Celsius (-240 degrees Fahrenheit) at the poles.

4 Looking for life
One of the main scientific goals of going to Mars will be to answer questions about life on the Red Planet.

5 Underground water
Water ice lies just a few metres beneath the surface of Mars down to at least its mid-latitudes and should be easily accessible.

6 Weather station
When on Mars, astronauts can study the atmosphere and weather, looking out for huge dust storms that could rapidly engulf the landing site.

7 Self-supporting
An inflatable greenhouse could be used to grow crops, though nobody knows how well plants will grow in Martian dirt.

8 Longer days
The length of a Martian solar day, or sol, is 24 hours and 39 minutes. Astronauts will need special Mars watches that factor in this extra time.

9 Landing craft
The Mars Direct mission proposed sending habitation modules to Mars with each new crew, eventually building up to the first settlement on the Red Planet.

10 Geology
The rocks and dirt on Mars can tell us a lot about the past climate in their local environment. Some of the first Martian astronauts may well be geologists.

© NASA

crews into space. "There are issues of radiation and the well-known properties of the Martian atmosphere, which I became aware of as a co-investigator with James Van Allen, my late mentor, on the first US mission to Mars, Mariner 4, in 1965," Krimigis says. Luckily, other experiments can be carried out on the International Space Station. "The principal challenges have to do with the ability of human crews to withstand the long-term effects of weightlessness, radiation exposure and isolation over such a long period of time. Here the experience of continued studies with crews on the space station is essential in answering some of these questions," Krimigis adds.

Travelling to the Moon will also help future missions to Mars. NASA's Moon to Mars endeavour aims to establish a long-term lunar presence, and that, according to the space agency's administrator Bill Nelson, will enable NASA to "prepare for humanity's next giant leap to the Red Planet". The knowledge and skills gained on the Moon will help launch astronauts to Mars sometime after the late 2030s. But a lot will depend, as always, on funding.

Humphrey Price, chief engineer of NASA's robotic Mars Exploration Program, tells us that "plans for the Moon to Mars program are advancing at a pace that is constrained by funding allocations from Congress and by the progress being made by the commercial providers to support the return of astronauts to the Moon". With sufficient, timely funding, it's suggested that a crewed mission to orbit Mars without landing could be on the cards as early as 2033, taking advantage of a rare planetary alignment, as Mars will be at opposition. But it's touch and go to have everything ready in just nine years, even if Apollo went from zero to Apollo 8's orbit of the Moon in the same time frame. "It's my opinion that a 2033 crewed Mars orbital mission is feasible, but only if that is given priority by Congress and if adequate funding was provided to develop the vehicles needed in parallel with the Artemis program to return astronauts to the Moon," says Price, who has drawn up plans for creating a base on Mars. "An alternative could be a 2035 short-duration flyby mission to both Mars and Venus. This is attractive because it would only have a 1.5-year total trip time."

To ensure NASA is ready for such a possibility, the space agency has been working on advanced propulsion systems that would be used to send astronauts to Mars alongside inflatable landing gear to bear the weight of heavy equipment, adaptable spacesuits, homes and labs on wheels, surface power systems and laser communication systems to quickly send data back to Earth. It has been important to consider what astronauts could achieve on Mars, with scientists coming up with numerous experiments that could tell us more about the planet.

But NASA isn't operating alone. China is also keen to send astronauts to Mars, and reckons it could do so in 2033. SpaceX, meanwhile, wants to get missions going this decade, and the private sector is also involved in other ways. The Orion reusable crewed spacecraft used in NASA's Artemis program has been designed by Lockheed Martin and Airbus Defence and Space. The Space Launch System (SLS) will launch Orion, and both are important for a Mars mission. "The Orion and SLS vehicles are already in a state of development to support the schedule for an orbital or flyby mission to Mars. What would still be needed are a Mars Transit Habitat (MTH) and propulsion modules for the mission," says Price.

"It's my opinion that a 2033 crewed Mars orbital mission is feasible, but only if that is given priority" Humphrey Price

Again, money matters. "Contracts for commercial providers of the MTH are already in place, but the development of flight vehicles would need to be funded by Congress," Price continues. "The propulsion modules could be developed using existing technology systems, which could be provided commercially or by international partners, but the limiting factor would be a commitment for the mission and funding."

Funding and time are certainly of the essence if we're to see missions to Mars sooner rather than later. There's so much to be done, with lots of experiments and testing that need to be carried out before a human could even step on board a

Former NASA administrator Jim Bridenstine talking about sending astronauts to the Moon and Mars in 2019

A CHAPEA crew member embarking on a mission inside the simulated Mars habitat

The ultimate aim is to get humans on Mars, but whether that will be in the 2030s or the 2040s is anyone's guess

MOXIE's principal investigator Michael Hecht working on the technology that has extracted oxygen from the Martian atmosphere

spacecraft en route to the Red Planet. "Prior to the mission, it would be important to test a prototype version of the MTH in low-Earth orbit and/or at the lunar-orbiting Gateway that's scheduled for launch in 2027," Price says. "It would also be important to conduct long-duration missions with astronauts at the Gateway to characterise the effects of galactic cosmic radiation on the crew."

Realistically, the need for such preparations is going to have an impact on the potential time frame for a Mars mission, which Jim Reuter, associate administrator for NASA's Space Technology Mission Directorate, says is more likely to be around 2040. Even then, he suggests that's "an audacious goal for us to meet". A Moon presence would have to have been established by that point because it's set to be a stepping stone for Mars, and while that is likely, plenty of other factors come into play – one of which is desire.

Priorities often chop and change, and that was the case under the gaze of Donald Trump, who actually prioritised a Mars mission over one to the Moon. "We did that 50 years ago," he tweeted of the latter. As such, it can be difficult to predict which way an administration will go, with politics and cost inevitably playing a big part in the decision-making process. It's also likely to have an effect on the scale of NASA's ambition – landing is always expensive, as witnessed by the spiralling costs of the Mars Sample Return mission. "Absent of a compelling scientific argument, it would entail a strong political will for all of humanity to move forward with expansion to Mars as a matter of the next frontier in the destiny of humankind," says Krimigis. "The cost would be terrific – some estimates place it at a trillion dollars, at least. Exploration with a human crew may happen, but a colony on Mars? No way, at least for a very long time!"

David Crookes

Science and technology journalist

David has been reporting on space, science and technology for many years, has contributed to many books and is a producer for BBC Radio 5 Live.

COLONISING

What will it take to create a supercity on Mars?

SpaceX also has its sights on Mars, but the company's ambitions stretch much further. It wants to create a self-sustaining settlement by around 2050 and plans to have a million people on Mars by the end of the century. But is that possible? Not in the time frame suggested, argues Krimigis. "First and foremost, you have to consider the effects of the radiation environment on the crew, both during transit and on the surface," he says. "It's well known that there is no effective way of shielding against galactic cosmic rays during transit or on the Martian surface, and their long-term harm to humans is well-known.

"Further, the occasional solar eruptions and accompanying emissions of high-energy protons are very difficult to shield against, and certainly not during transit to the planet – the required shelter within the spacecraft would be prohibitively heavy in terms of total launch mass, although not insurmountable as more capable launch vehicles are developed. Space weather predictive capability is also still in its infancy, so we can know for certain what the Sun will do, especially over long periods.

"Secondly, the thin Martian atmosphere of carbon dioxide is hardly ideal for surface activities by a human crew. Coupled with the absence of a Martian magnetic field to protect against radiation, you'll need to construct essential structures for long-term stays underground. Although all of these things are technically possible, in addition to the cost, they bring into question the value of a colony on Mars in the first place. That's why I believe a colony on Mars is a distant dream at best."

FOCUS ON

NASA'S PERSEVERANCE ROVER FINDS POSSIBLE SIGNS OF ANCIENT RED PLANET LIFE

Further analysis is needed, but a rock contains potential evidence that life once existed on Mars in the distant past

Reported by Sharmila Kuthunur

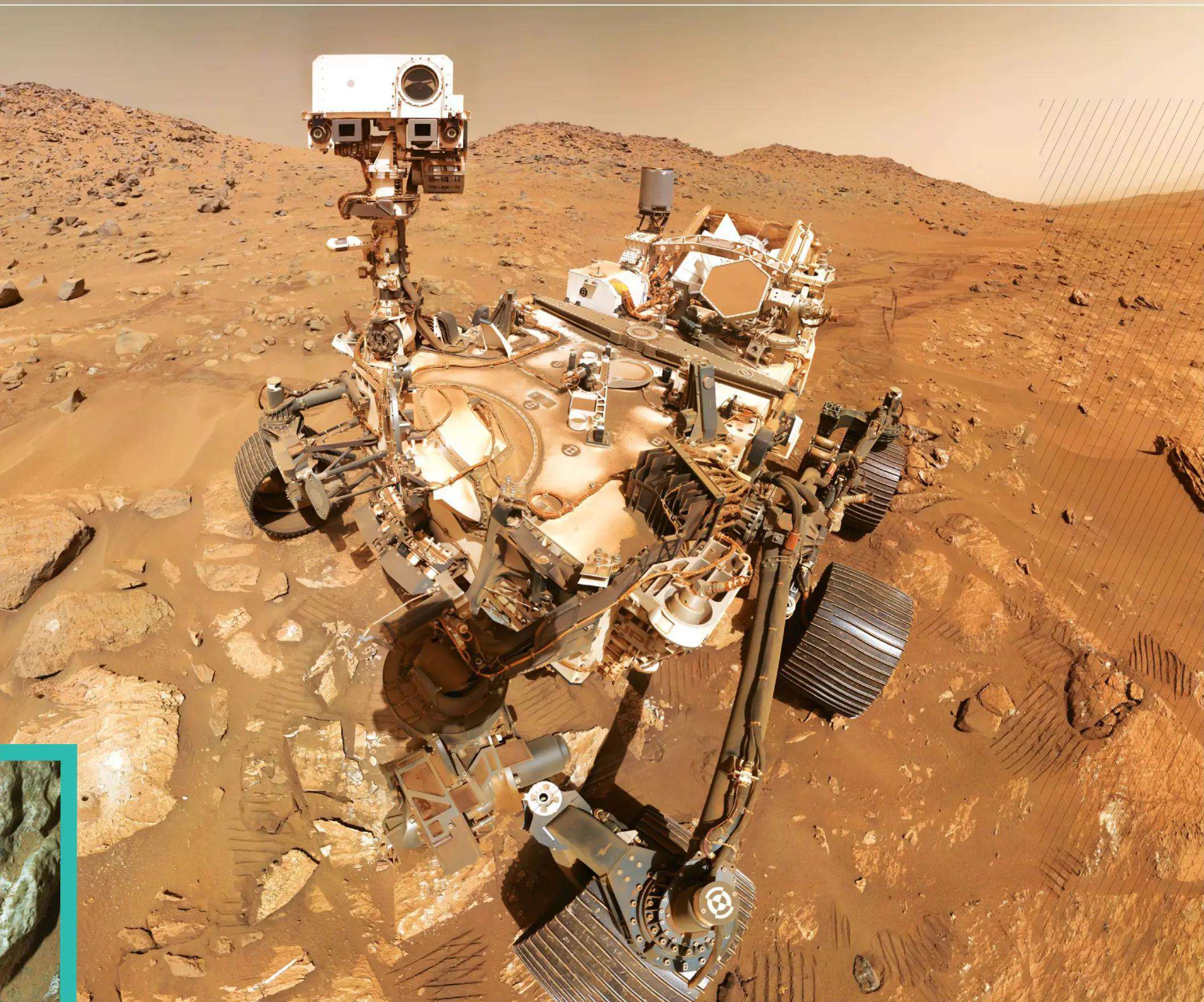
NASA's Perseverance rover may have found signs of ancient life in a rock on Mars. The mission team's scientists are ecstatic, but remain cautious, as further analysis is needed to confirm the discovery. The rover has come across an intriguing, arrowhead-shaped rock that hosts chemical signatures and structures that could have been formed by microbial life billions of years ago, when Mars was significantly wetter than it is today. Inside the rock, which scientists have nicknamed Cheyava Falls, Perseverance's instruments detected organic compounds, which are precursors to the chemistry of life as we know it. Wisping through the length of the rock are veins of calcium sulphate, mineral deposits that suggest water – also essential for life – once ran through the rock.

The rover also found dozens of millimetre-sized splotches, each surrounded by a black ring and mimicking the appearance of leopard spots. These rings contain iron and phosphate, which are also seen on Earth as a result of microbe-led chemical reactions. "These spots are a big surprise," David Flannery, an astrobiologist and member of the Perseverance science team from the Queensland University of Technology in Australia, said. "On Earth, these types of features in rocks are often associated with the fossilised record of microbes living in the subsurface."

"We've never seen these three things together on Mars before," Morgan Cable, a scientist on the Perseverance team, said. Cheyava Falls sits at the edge of an ancient 400-metre (1,312-foot) wide river valley named Neretva Vallis. Scientists suspect this ancient channel was carved out long ago due to water gushing into Jezero crater; Neretva Vallis runs along the inner wall of this region. In one possible scenario, mud that already possessed organic compounds got dumped into the valley and later cemented into the Cheyava Falls rock, which Perseverance sampled on 21 July. A second episode of water oozing into the formed rock would have created the object's calcium sulphate veins and black-ringed spots.

But to be clear, the rock's visible features aren't irrefutable evidence of ancient microbial life on Mars – not yet, at least. It is possible, for instance, that the observed calcium sulphate entered the rock at

^ Perseverance has discovered a rock on Mars that may have once hosted microbial life



uninhabitably high temperatures, perhaps during a nearby volcanic event. However, whether such non-biological chemical reactions could have resulted in the observed black-ringed spots is an open question, the scientists say. "This trip through the Neretva Vallis riverbed paid off as we found something we've never seen before, which will give our scientists so much to study," Nicola Fox, the associate administrator of NASA's Science Mission Directorate, said.

"We have zapped that rock with lasers and X-rays and imaged it literally day and night from just about every angle imaginable," Ken Farley, Perseverance project scientist at the California Institute of Technology, said. "Scientifically, Perseverance has nothing more to give." To fully grasp what really unfolded in the ancient Martian river valley billions of years ago, scientists are keen to get the Cheyava Falls sample to Earth, where it can be scrutinised with powerful instruments that Perseverance's limited suite doesn't have.

The complex Mars Sample Return effort, however, has run into many snags in recent months after its costs spiked to $11 billion (£8.5 billion). In its current form, the program requires multiple launches to Mars to place a vehicle on the Red Planet, after which either Perseverance will travel to the vehicle and drop off its collected samples, or pop those samples over to a retrieval helicopter that can complete the handoff. Then an ascender would launch the samples into orbit, where a spacecraft would collect them and return them to Earth.

"On Earth, these types of features in rocks are often associated with the fossilised record of microbes living in the subsurface" David Flannery

THE TEN BEST IMAGES TAKEN FROM THE INTERNATIONAL SPACE STATION

The orbiting laboratory has a unique view of Earth and its surroundings

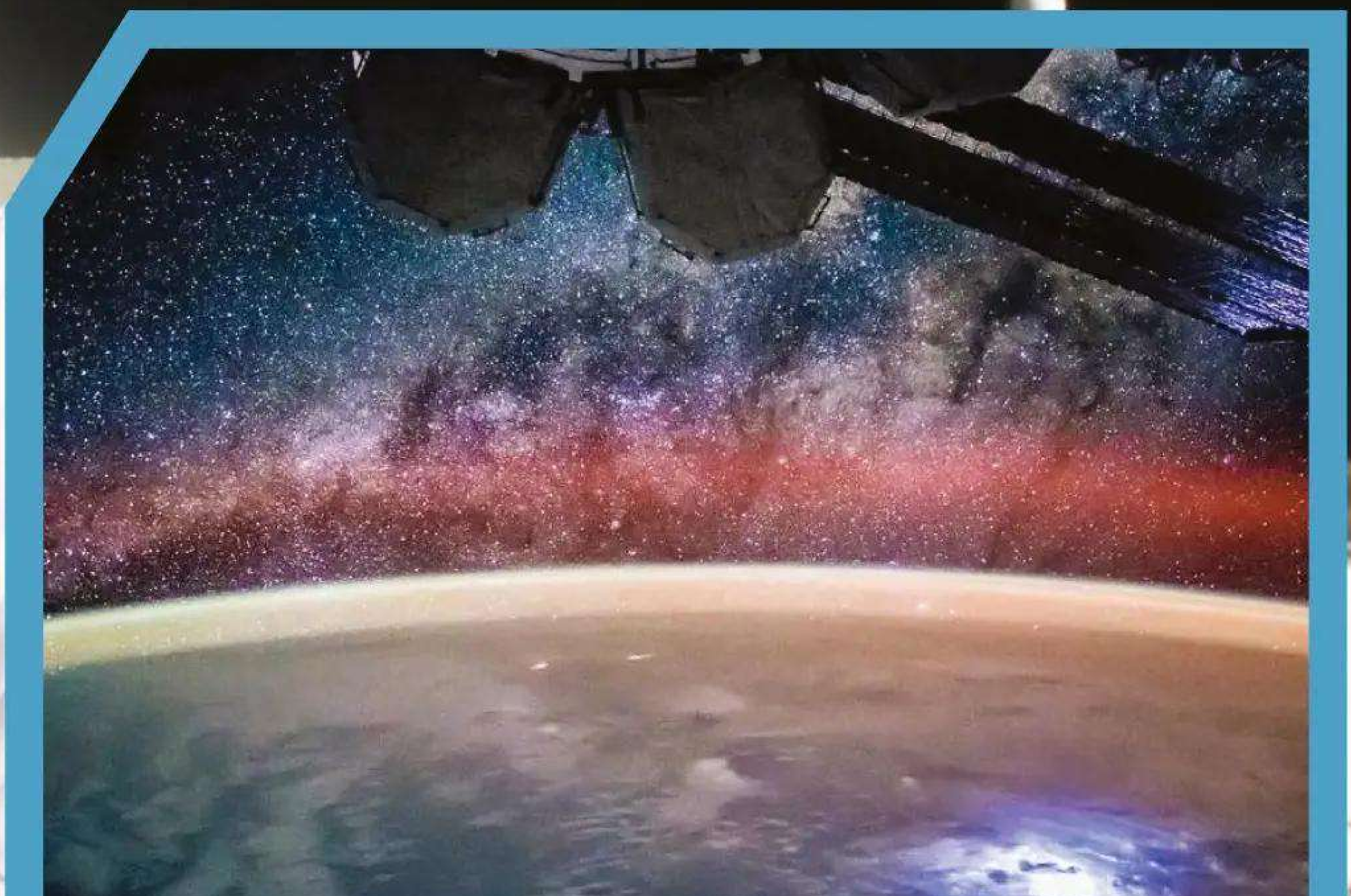
Written by Stuart Atkinson

JUST STEPPING OUT FOR A WALK

Astronauts train for many years for the chance to go to space with no guarantee of actually flying, so being given a place on a mission to live on the International Space Station (ISS) for a few months is a dream come true. But some astronauts get to do even more – they wriggle into a spacesuit and go outside on an extravehicular activity (EVA), or spacewalk. This image, taken on 23 May 2017 during the 201st spacewalk of the ISS program, shows NASA astronaut Jack Fischer waving at his colleagues inside the space station as he worked outside the US Destiny laboratory. Fischer was attaching antennae to the exterior of the ISS during an unplanned EVA to repair and replace a failed computer data relay box. Luckily, there was no malfunctioning computer to refuse to let him back inside...

A SKY FULL OF STARS

Whenever NASA posts an image of a beautiful view from the ISS, within minutes conspiracy theorists are declaring it's a fake. One of their favourite comments is "Where are the stars? The sky should be full of stars!" This comes down to a lack of understanding of basic photography. The vast majority of images taken from the ISS are taken when it's in daylight, and show Earth, or the ISS structure itself, brightly lit by the Sun. The exposures are far too short – fractions of a second – to record the faint stars in the sky. Exposures long enough to show the stars would burn out Earth and the ISS. However, the astronauts aboard the ISS have magnificent views of the stars after sunset, and they do occasionally post images showing that view. This one, taken on 9 August 2015 by a member of the Expedition 44 crew, shows the star clouds of the Milky Way and dark lanes of dust across them.

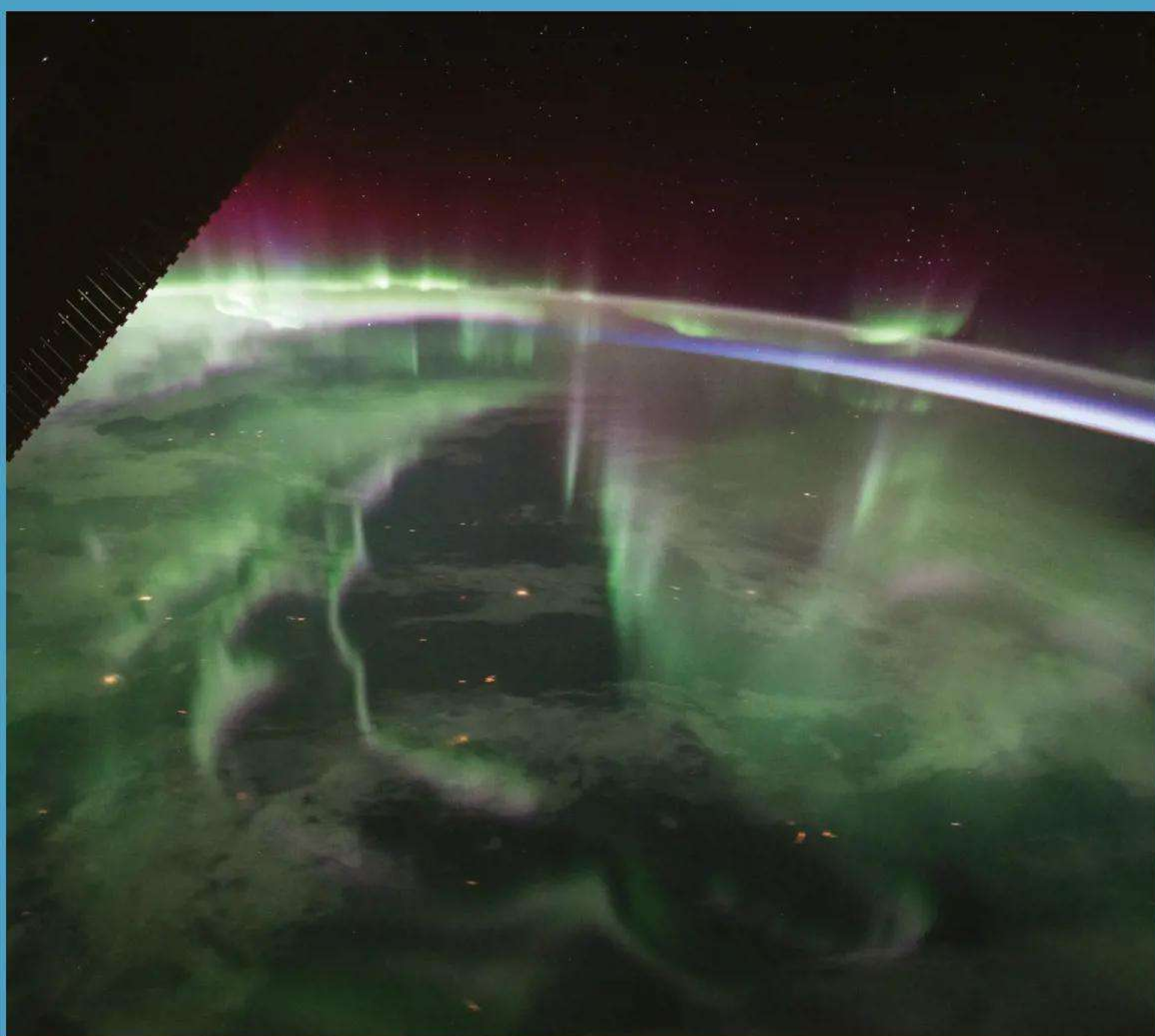


SHUTTLE ORBITER FLY AROUND

Today we are used to seeing astronauts flying to and from the ISS inside small capsules, like the Russian Soyuz and SpaceX's Crew Dragon. But between 1998 and 2011 a fleet of sleek snow-white Space Shuttle orbiters carried them. Much larger than the capsules used today, the reusable orbiters were carried piggyback-style into space by rockets, then landed on runways like aeroplanes at the end of their missions. Taken in July 2006, this spectacular image shows the Space Shuttle Discovery approaching the International Space Station. Before docking, Discovery flew around the ISS, posing for a number of inspection photos so the astronauts aboard the ISS could check for any damage to the spacecraft's heat tiles. Clearly visible are the orbiter's open payload bay doors and the European Space Agency's Leonardo Multipurpose Logistics Module in its huge cargo bay.

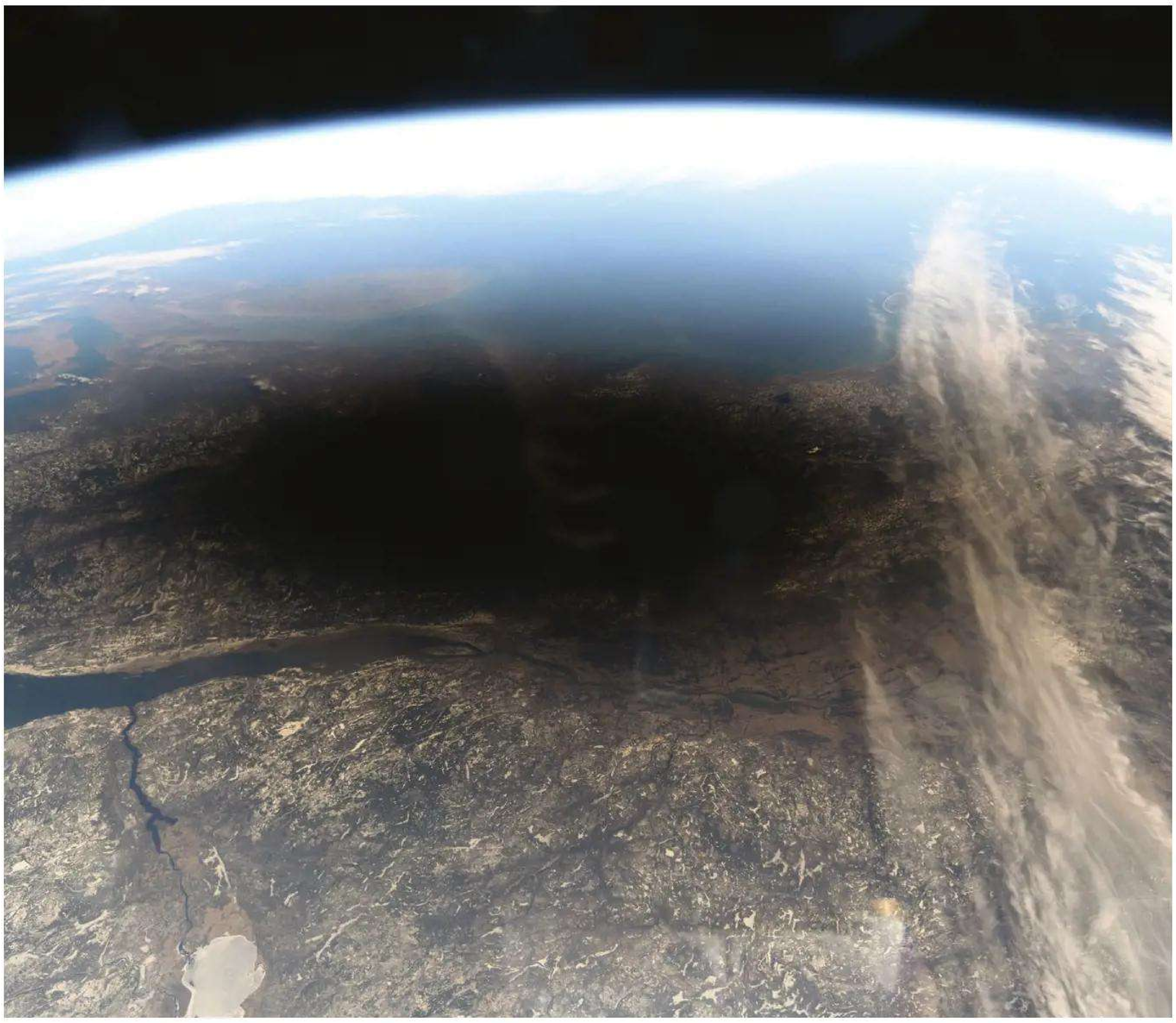
FLYING THROUGH THE NORTHERN LIGHTS

Looking up at a bright display of the northern lights swooshing and swaying in the night sky is such an amazing and moving experience that people spend a lot of time and money 'chasing' aurorae, travelling to countries in the far north in the hope of catching even just a glimpse of them. But crews on the ISS can see the northern lights just by looking out their window, and they're beneath them, not above. Sometimes they even fly through them. The views of aurorae from orbit are simply magical. Crews can look down and see rays of red and pink shooting up from beneath them like the beams of searchlights, and curtains of green rippling beneath them too. This image was taken from the ISS on 15 September 2017 as the space station flew over Canada.



IN THE SHADOW OF THE MOON

For a few fleeting minutes on 8 April 2024, a vast swathe of North America came to a halt as millions of people stopped what they were doing to watch one of nature's greatest spectacles – a total solar eclipse. As the Moon passed in front of the Sun, it cast a round shadow 160 kilometres (99 miles) across onto Earth, which raced across its surface at 1,930 kilometres (1,200 miles) per hour. People standing in that shadow saw the sky darken and the Sun vanish, replaced by a black hole surrounded by a feathery halo of silver light. Up on the ISS, the astronauts paused their busy day to watch the eclipse from above. This wonderful image shows Earth's shadow covering portions of the American state of Maine and the Canadian provinces of Quebec and New Brunswick near the end of the eclipse.



ARRIVAL OF A DRAGON

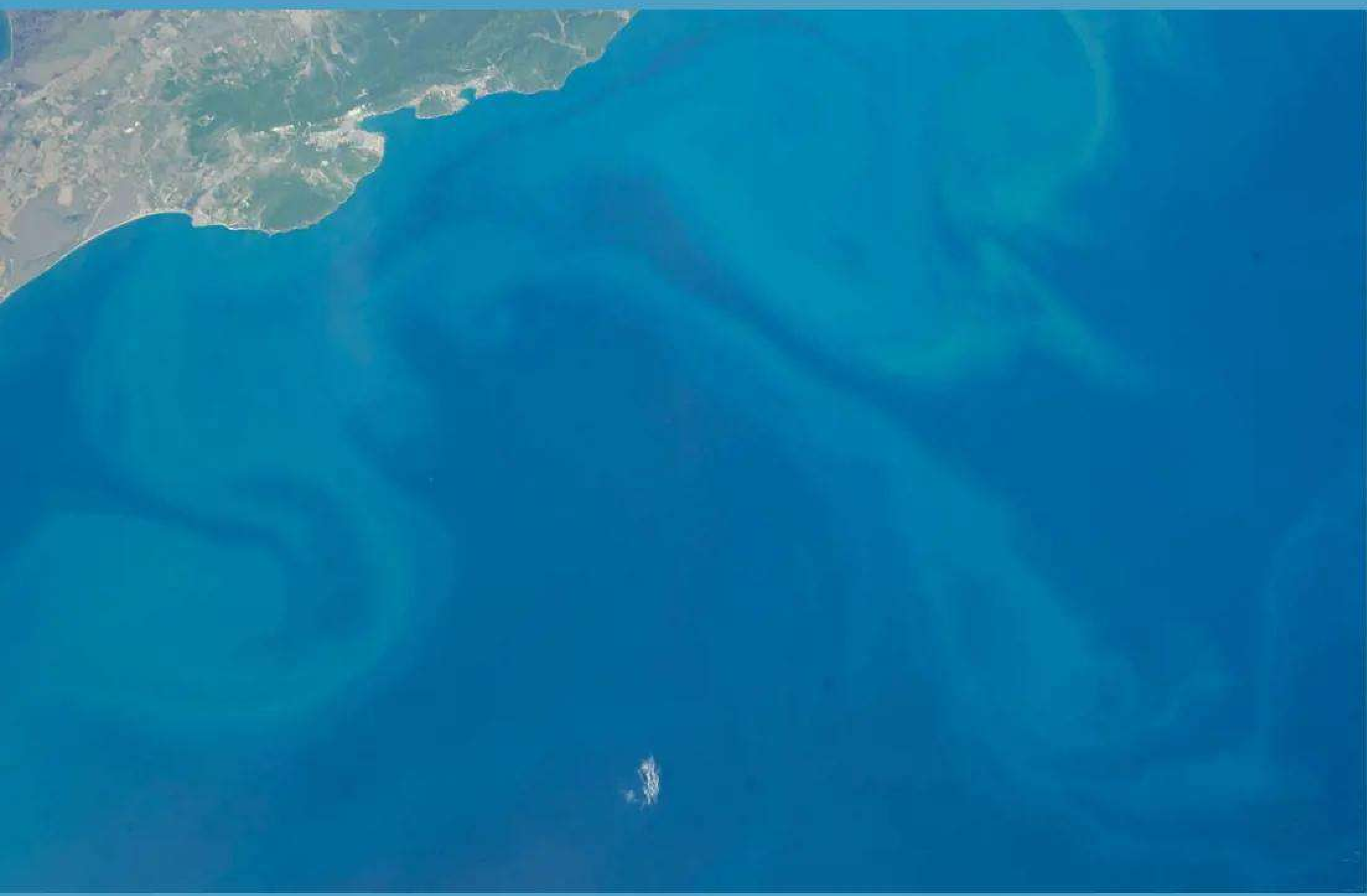
Looking like a futuristic spaceship from a science-fiction film, SpaceX's reusable Crew Dragon capsule is much sleeker and shinier than the Russian Soyuz capsules that carried crews to and from the ISS after the final Space Shuttle flight in 2011. Crew Dragons are carried into space atop Falcon rockets, and each one can be flown many times. They usually carry four astronauts, but they can carry up to seven if needed, and they contain high-tech screens and consoles. This January 2021 image shows a newly arrived Crew Dragon capsule docked to the Harmony module's forward-docking adaptor. Its nose cone is open, revealing the docking mechanism that secured it to the space station.

VOLCANIC ERUPTION

Astronauts aboard the ISS have a spectacular and unique view of Earth, and understandably spend a lot of time photographing it. But they don't just take pretty pictures – their photographs are invaluable to scientists who study our planet's weather systems and geology. In June 2009, one of the members of Expedition 20 took this stunning image of Sarychev Peak on the Kuril Islands in Russia erupting. It clearly shows a huge plume of smoke, steam and ash billowing up out of the volcano, creating a hole in the layers of cloud above it.

BRIGHT LIGHTS OF LONDON

When the ISS is in daylight, astronauts looking down on Earth enjoy spectacular views of its blue oceans, snow-capped mountains and glistening, meandering rivers. After sunset, the world below them is plunged into darkness, but soon lights appear in that darkness, like stars coming out on clear night, as the artificial lights of our towns and cities come into view, shining like clusters of blue and gold stars. This spectacular image, taken on 27 September 2015, shows London, England's capital city. The dark areas are the capital's famous parks.



THE LIGHT OF LIFE

It's a well-worn cliché that when astronauts look down at Earth from above, they can see no borders and no countries – just one world. But when members of ISS expeditions look back at Earth, one thing they can see very clearly is life. They see lush forests spread out on the landscape like green carpets and the cross-hatch patterns of cultivated farm fields. They also see life in the oceans in the form of blooms of plankton. This image, taken in May 2015, shows a huge plankton bloom in the Black Sea, which connects Eastern Europe and Asia Minor. Carried through the water by currents, the phytoplankton appear as blue and turquoise streams and swirls in the darker water.

STARING A HURRICANE IN THE EYE

Many of us are fascinated by the weather, and storms in particular. Every time a big thunderstorm occurs, social media is full of photos of forks of lightning zig-zagging dramatically across the sky. Some people take this fascination with meteorology to extremes and go on high-speed pursuits of tornadoes as they spin across Earth. But astronauts aboard the ISS can storm watch from the comfort of the observation Cupola, looking down on hurricanes as they whirl silently across the world below. This beautiful image, taken by astronaut Ed Lu on 15 September 2003, shows Hurricane Isabel as it headed for the east coast of the US. By then it was a Category 3 storm, but earlier it had been a much more powerful and dangerous Category 5, with winds estimated at 257 kilometres (160 miles) per hour.

FOCUS ON

THE ARTEMIS IV CREW WILL BE THE FIRST TO USE NASA'S MOON-ORBITING GATEWAY

The crew will include one European astronaut

Reported by Sharmila Kuthunur

The first mission to make use of NASA's Gateway space station will be Artemis IV, now scheduled to launch in 2028. NASA and its international partners see Gateway as a key platform to support the agency's Artemis Moon program and to build the technology required for future deep-space missions. Although the first elements of the small space station are expected to launch before the Artemis III mission lifts off in 2025 or 2026, NASA previously said that those astronauts will not use Gateway to "make that mission have a higher probability of success."

Instead, the astronauts of the Artemis IV mission, who will attempt the program's second landing on the Moon in 2028, will be the first ones to live and work in the small lunar outpost. The first two elements of the orbiting space station – one of which is the Habitable and Logistics Outpost (HALO), where astronauts will live and carry out research – are scheduled to be integrated on Earth and launched together in late 2025. By the time the first crewed mission arrives at the small space station, NASA plans to add a second habitable module.

The consequent Artemis V mission, currently scheduled for 2029, will carry a refueller for the lunar outpost. The European Space Agency (ESA), in partnership with Japan, will be providing the refuelling module as well as the second habitat module. In

A LUNAR GATEWAY

1 Orion spacecraft
This module brings astronauts from Earth and returns them home at the end of a mission.

2 External robotics
The Canadian Space Agency will provide an external robotic arm, similar to the one on the ISS.

return, European astronauts will receive three flight opportunities on board Artemis missions to get to and work on the lunar outpost and touch down on the Moon. Two of those missions will be Artemis IV and V, with the third yet to be announced.

While Gateway will serve as a compact home for astronauts, it's being built so that it can operate autonomously without a crew for up to three years between missions. That autonomy is quite different from the International Space Station (ISS), which has been continuously crew-occupied for over 20 years and is scheduled to retire in 2030. "It's not a stretch to say that Gateway is very much a part of the ISS legacy," said Stephanie Dudley, the mission integration and utilisation manager for Gateway.

The crew size on the two space stations will be different, too. While the ISS has hosted a maximum of 13 astronauts at one time, Gateway, which is a fifth of the size of the ISS by volume, caps out at four crew members for a maximum of 90 days. Dudley emphasised that science experiments performed on Gateway will leverage the station's unique position around the Moon and will provide results even without a crew being present. So far, the initial research experiments announced last year fit this criteria. Taking advantage of Gateway's orbit far away from Earth's protective magnetic field, three instruments will study risks due to radiation from the Sun and from cosmic rays. Scientists hope this knowledge can help inform future long-term missions to the Moon and Mars.

3 SpaceX rocket
The core elements of HALO and PPE will be launched using SpaceX's Falcon Heavy rocket.

4 ESPRIT
The European System Providing Refuelling, Infrastructure and Telecommunications is being provided by the European Space Agency.

5 Logistics module
Various companies, starting with SpaceX, will provide robotic craft to resupply the station from Earth.

6 Power and Propulsion Element (PPE)
The PPE, built by Maxar Technologies, will be a 60-kilowatt solar-powered module providing electricity, communications and other services.

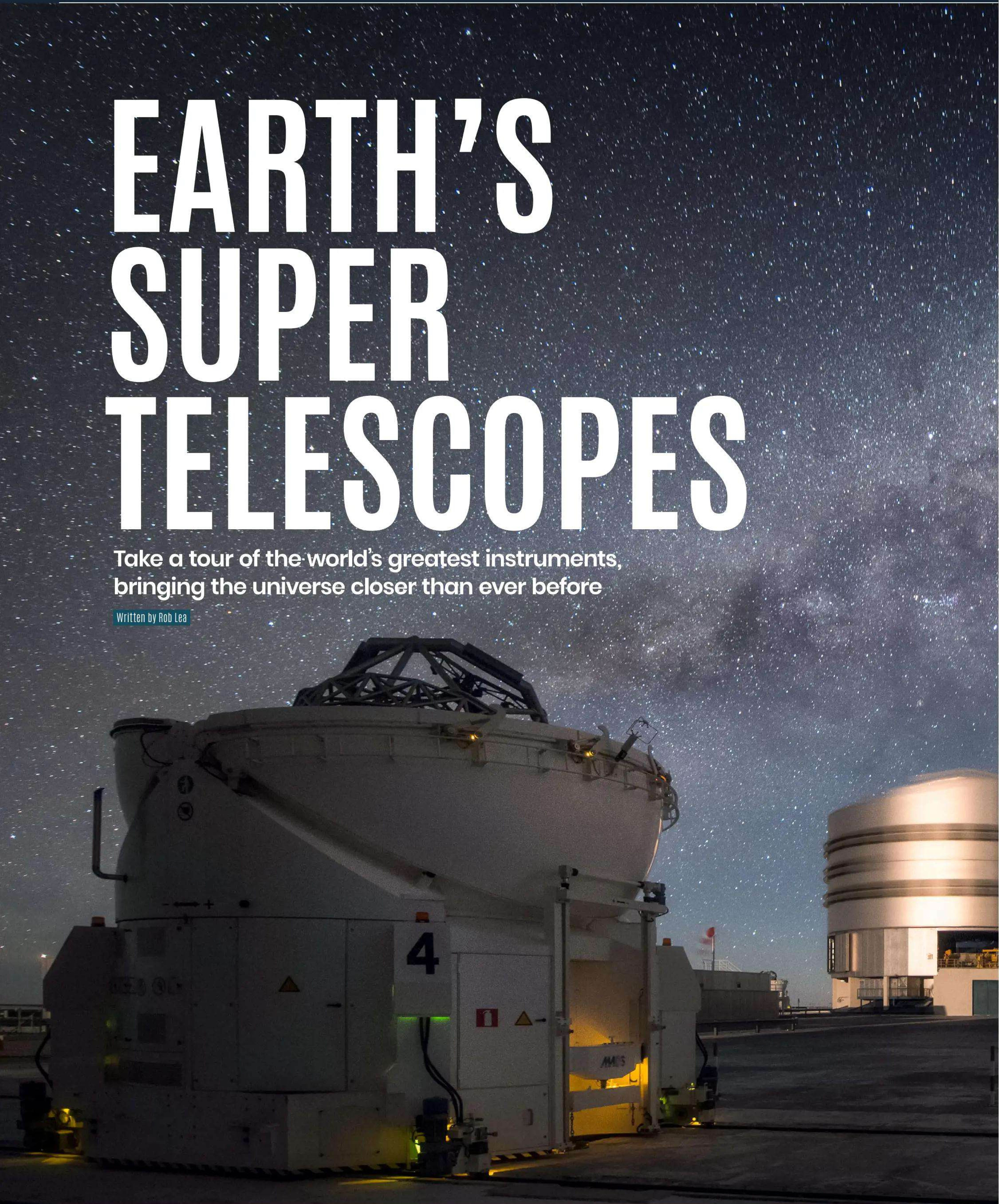
7 Habitation and Logistics Outpost (HALO)
HALO, under development by Northrop Grumman, will provide crew quarters for astronauts en route to the lunar surface.

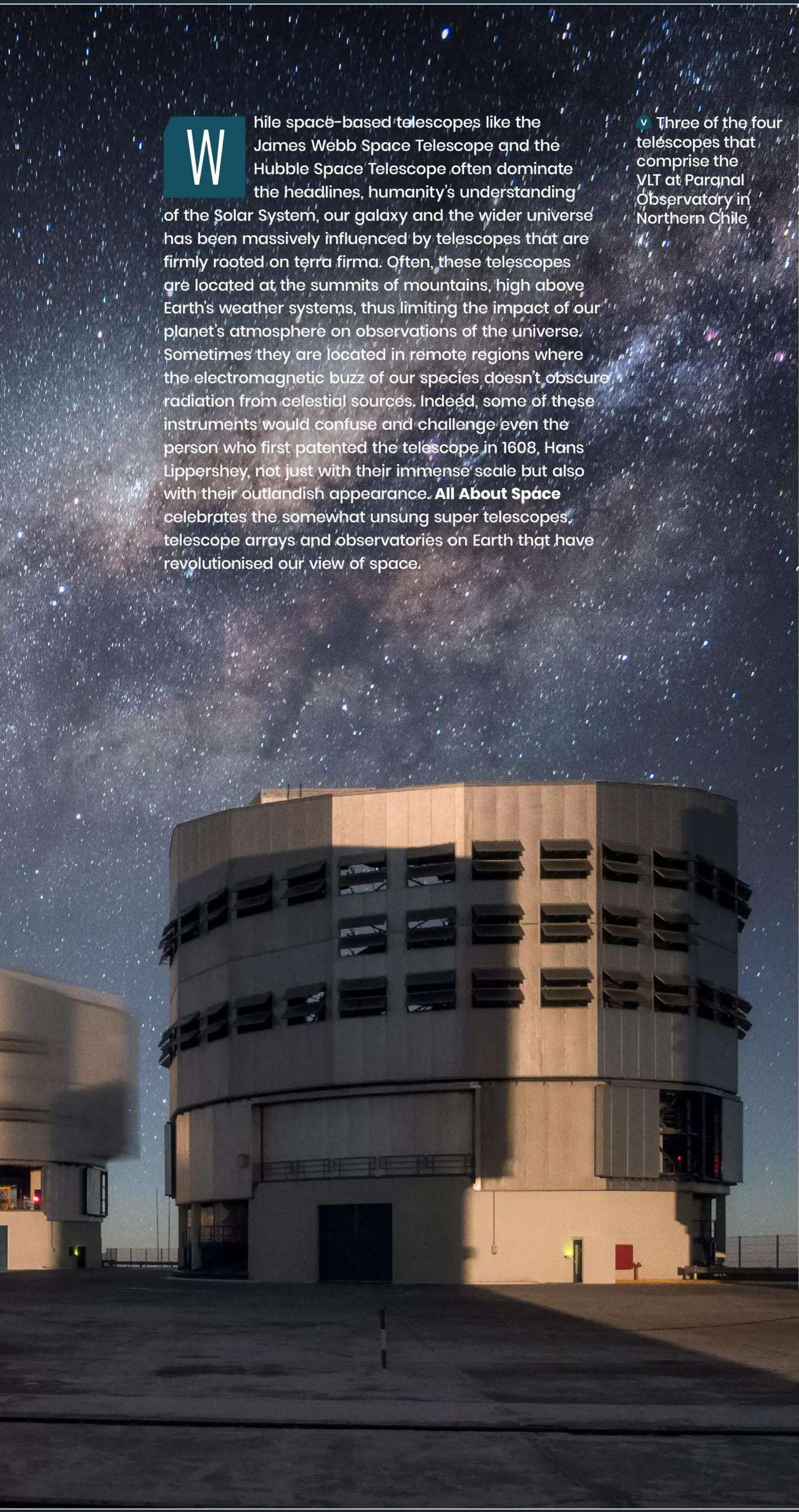
8 Human Landing System
The shuttlecraft to take astronauts down to the Moon's surface will be based on SpaceX's Starship vehicle.

EARTH'S SUPER TELESCOPES

Take a tour of the world's greatest instruments, bringing the universe closer than ever before

Written by Rob Lea





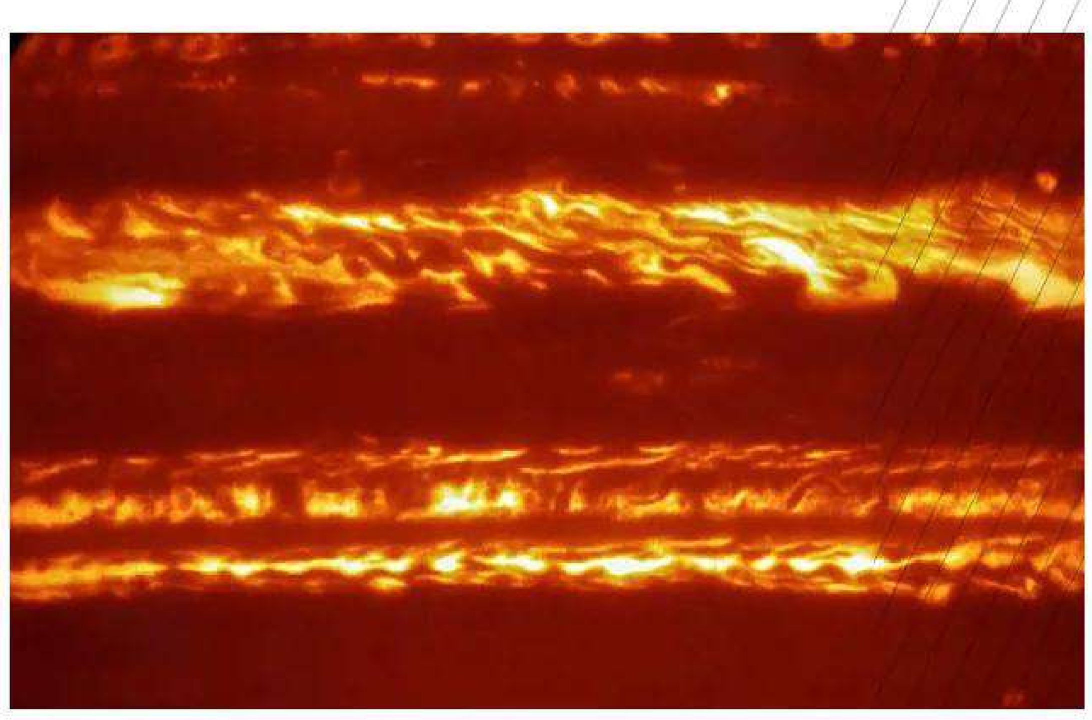
While space-based telescopes like the James Webb Space Telescope and the Hubble Space Telescope often dominate the headlines, humanity's understanding of the Solar System, our galaxy and the wider universe has been massively influenced by telescopes that are firmly rooted on terra firma. Often, these telescopes are located at the summits of mountains, high above Earth's weather systems, thus limiting the impact of our planet's atmosphere on observations of the universe. Sometimes they are located in remote regions where the electromagnetic buzz of our species doesn't obscure radiation from celestial sources. Indeed, some of these instruments would confuse and challenge even the person who first patented the telescope in 1608, Hans Lippershey, not just with their immense scale but also with their outlandish appearance. **All About Space** celebrates the somewhat unsung super telescopes, telescope arrays and observatories on Earth that have revolutionised our view of space.

Three of the four telescopes that comprise the VLT at Paranal Observatory in Northern Chile

VERY LARGE TELESCOPE

First light: 1998
Location: Cerro Paranal in the Atacama Desert, Chile
Type: Visible light
Diameter: Four Unit Telescopes with 8.2-metre (26.9-foot) diameter main mirrors and four movable 1.8-metre (5.9-foot) diameter auxiliary telescopes

The Very Large Telescope (VLT) is billed as the world's most advanced visible-light astronomical observatory and is the flagship facility for European ground-based astronomy. The four main telescopes of the VLT are named Antu, Kueyen, Melipal and Yepun, and they come together as a giant interferometer. The four telescopes can also be operated independently. One of the four telescopes of the VLT is capable of seeing faint astronomical objects with a visual magnitude of +30.0 in just an hour of viewing time. To put that into perspective, the faintest objects that can be seen with the naked eye are 4 billion times brighter than this. This means the VLT gives astronomers a precise and deep view of the cosmos.

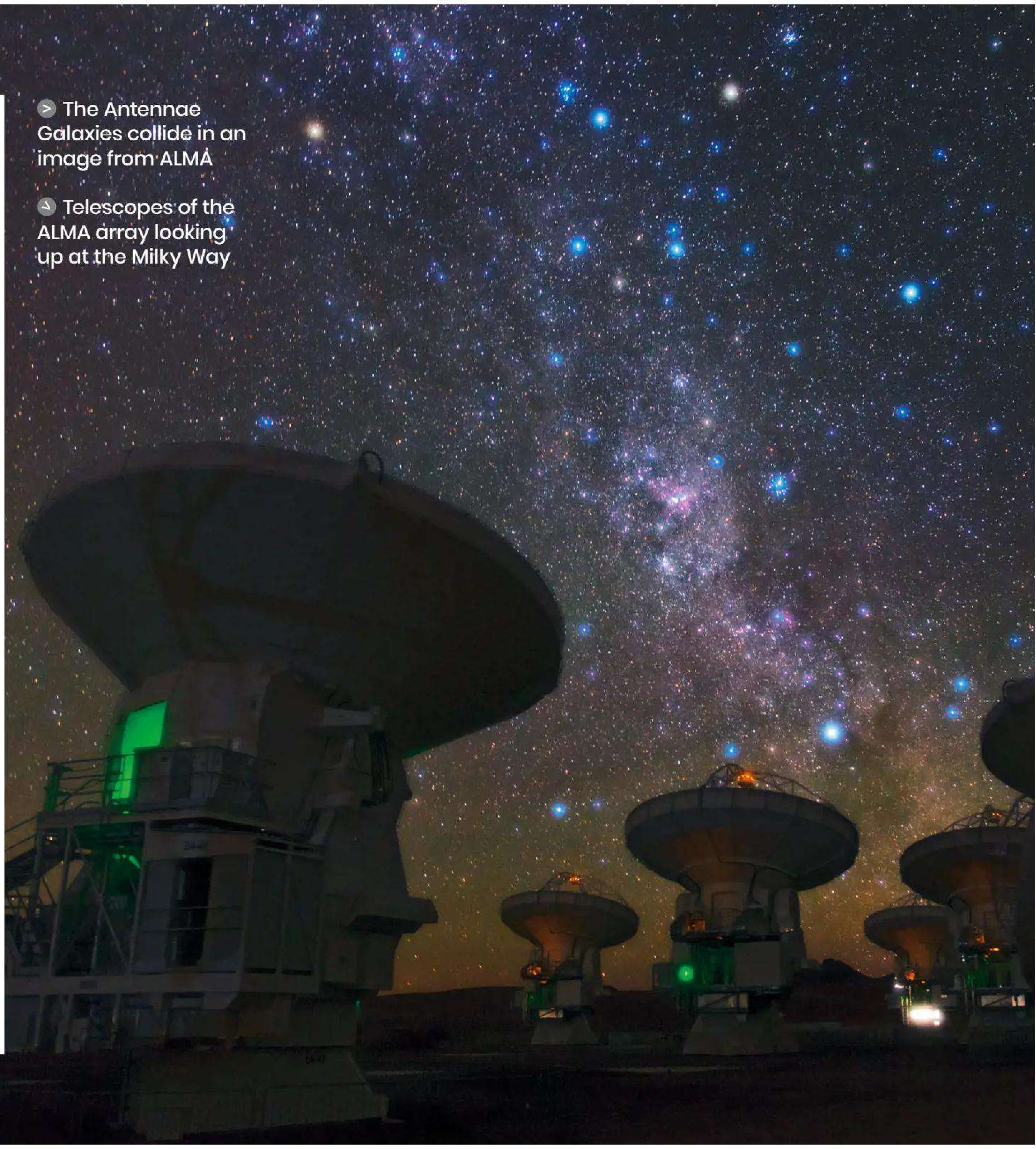


The Very Large Telescope snapped a fiery-looking Jupiter in 2016

ALMA

First light: 2011
Location: Chajnantor Plateau in the Atacama Desert, Northern Chile
Type: Infrared and radio
Diameter: 54 12-metre (39.4-foot) diameter dishes and 12 seven-metre (23-foot) dishes

The Atacama Large Millimeter/submillimeter Array (ALMA) is a collection of 66 telescopes located at an altitude of around 5,000 metres (16,404 feet) on the Chajnantor Plateau in the Chilean Andes. It's the world's most powerful telescope for studying submillimetre and millimetre-wavelength light that exists in the electromagnetic spectrum between infrared and radio. The antennae of this array are separated by as much as 6.2 kilometres (ten miles) from each other, but act as a single giant telescope. The antennae can be steered with great precision and pointed with an accuracy that is equivalent to spotting a golf ball at a distance of around 6.2 kilometres (ten miles) away. Searching the cosmos in light with longer wavelengths, and thus less energy than visible light, enables ALMA to investigate some of the universe's more cool objects, including the cool gas flooding into colliding galaxies that will eventually trigger a burst of star formation.



The Antennae Galaxies collide in an image from ALMA

Telescopes of the ALMA array looking up at the Milky Way

GEMINI TELESCOPES

First light: 1999 (Gemini North) and 2000 (Gemini South)
Location: Mauna Kea in Hawaii and Cerro Pachón in Chile
Type: Optical and infrared
Diameter: Twin 8.1-metre (26.6-foot) telescopes

With twin telescopes located in both the Northern and Southern Hemispheres of Earth, the two telescopes of the Gemini Observatory have a view of the entire night sky over Earth. Gemini North sits on Hawaii's inactive volcano Mauna Kea, 4,214 metres (13,825 feet) into the ideal dry and stable atmospheric conditions of the Pacific Ocean. The Gemini South telescope is located on Cerro Pachón, a mountain in the Chilean Andes, where it benefits from very dry air and negligible cloud cover. Both Gemini telescopes have mounted suites of four optical and infrared imagers and a wide range of optical and infrared capabilities, with technology like laser guide star adaptive optics and multi-object spectroscopy, allowing astronomers to explore the universe in incredible depth and detail. Rapid switching between instruments on the telescopes allows astronomers to shift to new astronomical targets in a matter of minutes.

FIVE-HUNDRED-METER APERTURE SPHERICAL TELESCOPE

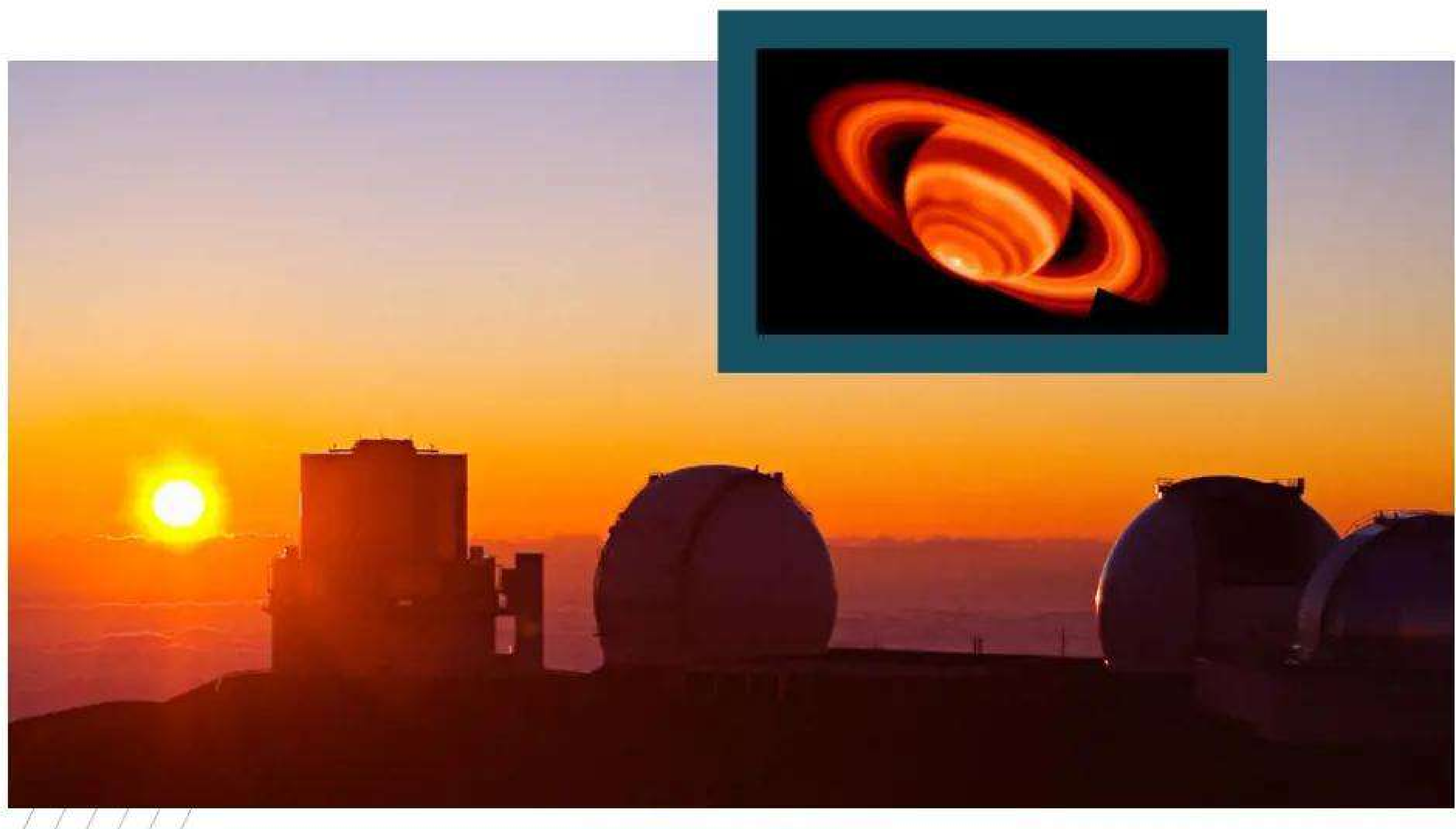
First light: 2016
Location: Dawodang depression in Pingtang County, Guizhou, China
Type: Radio
Diameter: 500 metres (1,640 feet)

The Five-hundred-meter Aperture Spherical Telescope (FAST) is located in a deep natural basin in Guizhou province in southwest China. The massive radio telescope requires radio silence within a 4.8-kilometre (three-mile) radius, which resulted in 8,000 people being relocated from their homes in eight villages around the facility as it was being constructed between 2011 and 2016. Taking its inspiration from the now-defunct Arecibo Observatory, which collapsed in 2020, FAST will spend the next few decades exploring space in radio waves and is expected to be the leader in radio astronomy for at least the next ten years. It has even been suggested that FAST could be the instrument capable of detecting signals from extraterrestrial life for the first time.

The telescopes of the W. M. Keck Observatory

The FAST radio telescope seen from the air

Gemini North is on Mauna Kea in Hawaii and Gemini South is on Cerro Pachón in Chile



KECK TELESCOPES

First light: 1993 (Keck I) and 1996 (Keck II)
Location: Mauna Kea, Hawaii
Type: Ultraviolet to infrared
Diameter: Twin ten-metre (32.8-foot) telescopes

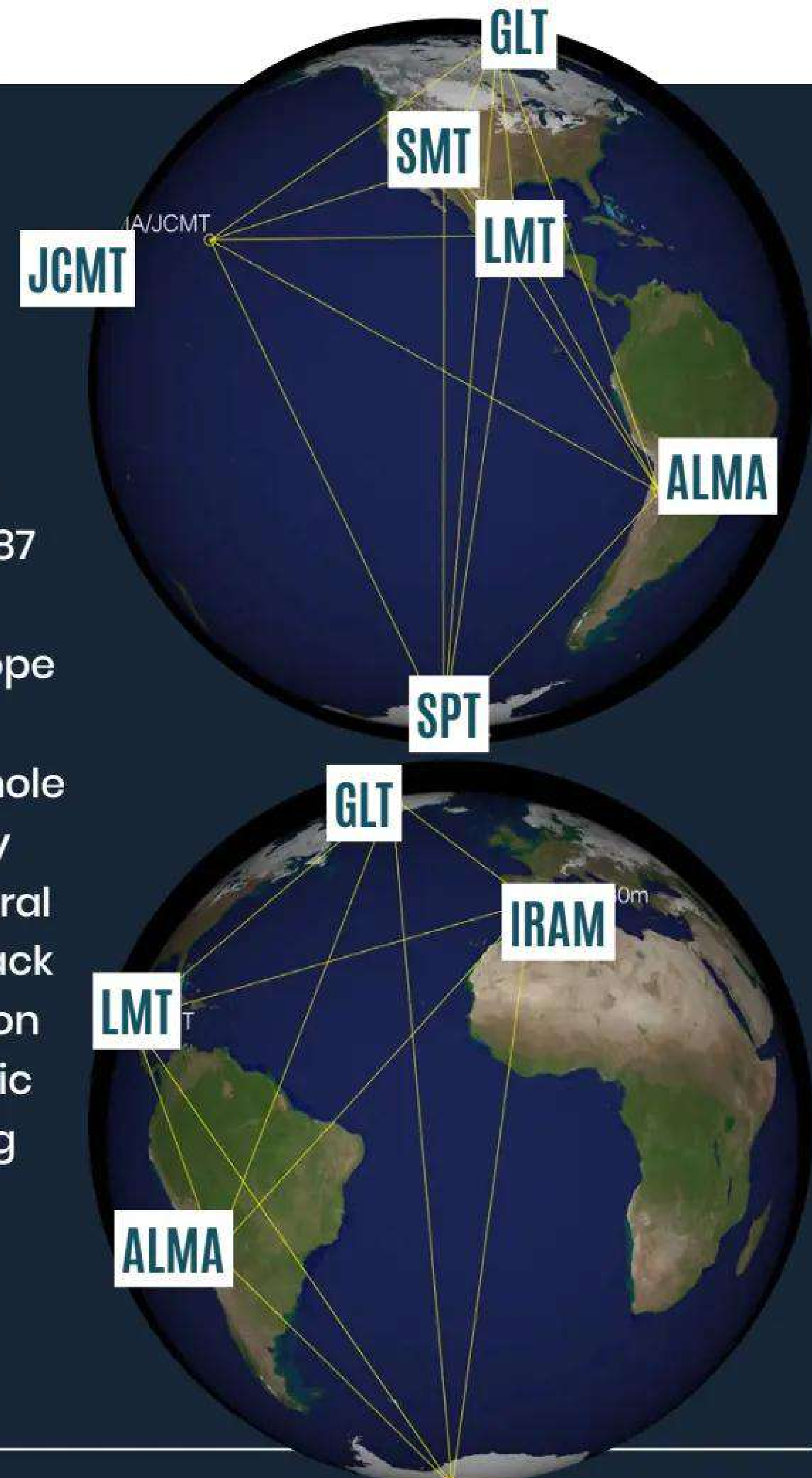
The two telescopes of the Keck Observatory, Keck I and Keck II, are located near the summit of Mauna Kea in Hawaii at an elevation of around 4,145 metres (13,599 feet), also taking advantage of the dry Pacific conditions. The twin Keck telescopes are the largest fully steerable optical-to-infrared telescopes on Earth and are able to see fainter and further into the cosmos than any other current research facility. The data supplied by the twin Keck telescopes has been integral in the study of planets outside the Solar System, or exoplanets, as well as being important in the study of objects within the Solar System.

EVENT HORIZON TELESCOPE

First light: Various **Location:** Global **Type:** Radio **Diameter:** Various

The Event Horizon Telescope (EHT) is an array of telescopes – including the ALMA Atacama Pathfinder Experiment, the Greenland Telescope (GLT), the Heinrich Hertz Submillimeter Telescope (SMT), the James Clerk Maxwell Telescope (JCMT) and the South Pole Telescope (SPT) Submillimeter Array – that come together to form a virtual telescope with a light-catching area the size of Earth. The EHT became famous in 2019 when it was revealed that this huge radio interferometer, the name for an instrument that merges two or more sources of light, had captured humanity's first image of a supermassive black hole and the region surrounding it.

The image of the supermassive black hole at the heart of the galaxy Messier 87 was followed by the EHT collaboration revealing in 2022 that the global telescope array had captured the first image of Sagittarius A*, the supermassive black hole at the heart of our own galaxy, the Milky Way. Since then, the EHT has been integral in determining the characteristics of black holes, such as measuring the polarisation of light caused by the powerful magnetic fields that surround them and observing powerful jets of matter that erupt from around feeding black holes.



SUBARU TELESCOPE

First light: 1998 **Location:** Mauna Kea, Hawaii
Type: Infrared **Diameter:** 8.2 metres (26.9 feet)

Another advanced telescope taking advantage of the summit of the extinct volcano Mauna Kea existing above the clouds is the Subaru Telescope, operated by the National Astronomical Observatory of Japan. The Subaru Telescope has a field of view that is 75 times wider than that of the Keck telescopes, which combines with an impressive light-gathering capability to make it ideal for deep and wide-view sky surveys. Atmospheric effects on the telescope are limited by the enclosure the Subaru Telescope sits within.

Subaru has the distinction of being one of the few state-of-the-art telescopes to have been outfitted with an eyepiece that allows it to be used with the naked eye. This was created to allow Princess Nori, the daughter of Emperor Emeritus Akihito and Empress Emerita Michiko, to look through it. The eyepiece was eventually replaced with more sophisticated equipment, with Subaru outfitted with instruments that also make it ideal for examining the cool dust that exists between stars and hunting for exoplanets. The telescope is even capable of determining the distribution of dark matter, the mysterious substance that doesn't interact with light but accounts for as much as 85 per cent of matter in the universe.

The Subaru Telescope under the stars

Subaru image of a large active star-forming region called Sh 2-209

VÍCTOR M. BLANCO TELESCOPE

First light: 1976
Location: Cerro Tololo, Chile
Type: Optical
Diameter: Four metres (13.1 feet)

Commissioned in 1974, the Víctor M. Blanco Telescope is a near replica of the Mayall Telescope on Kitt Peak, located at Kitt Peak National Observatory southwest of Tucson, Arizona. The telescope, named in honour of Puerto Rican astronomer Víctor Manuel Blanco and located at an altitude of 2,207 metres (7,240 feet), is the home of the Dark Energy Camera (DECam), making it part of the Dark Energy Survey (DES). This survey studies dark energy, the force that drives the acceleration of the expansion of the fabric of space and accounts for an estimated 68 per cent of the matter and energy in the universe. The Víctor M. Blanco Telescope contributes to this by measuring the shift in the wavelengths of light from thousands of exploding massive stars, or supernovae, as the expansion of the universe pushes them away faster and faster under the influence of dark energy.

Gran Telescopio Canarias over the clouds on the island of La Palma

The Víctor M. Blanco Telescope under the Milky Way

GRAN TELESCOPIO CANARIAS

First light: 2007
Location: Roque de los Muchachos Observatory on the island of La Palma
Type: Optical
Diameter: 10.4 metres (34.1 feet)

The Gran Telescopio Canarias is the largest optical and single-aperture telescope in the world. This reflecting telescope with a segmented primary mirror is located at the Roque de los Muchachos Observatory on the island of La Palma.

AUSTRALIAN SQUARE KILOMETRE ARRAY PATHFINDER

First light: 2012 **Location:** Western Australia
Type: Radio **Diameter:** 36 12-metre (39.3-foot) antennae

Located north of Perth and deep in the Western Australian outback, the Australian Square Kilometre Array Pathfinder (ASKAP) uses novel technology to operate at extremely high survey speeds. This makes it adept at hunting the sky for celestial objects in radio waves. The rapid survey speed comes from the 36 antennae – each with a 30-square-degree field of view – that together provide a wide field of the southern sky. The survey capability of the array was validated by the Rapid ASKAP Continuum Survey beginning in 2020, during which the telescope mapped 3 million galaxies across the entire southern sky in a record-breaking 300 hours, one-third of which had never been seen before.

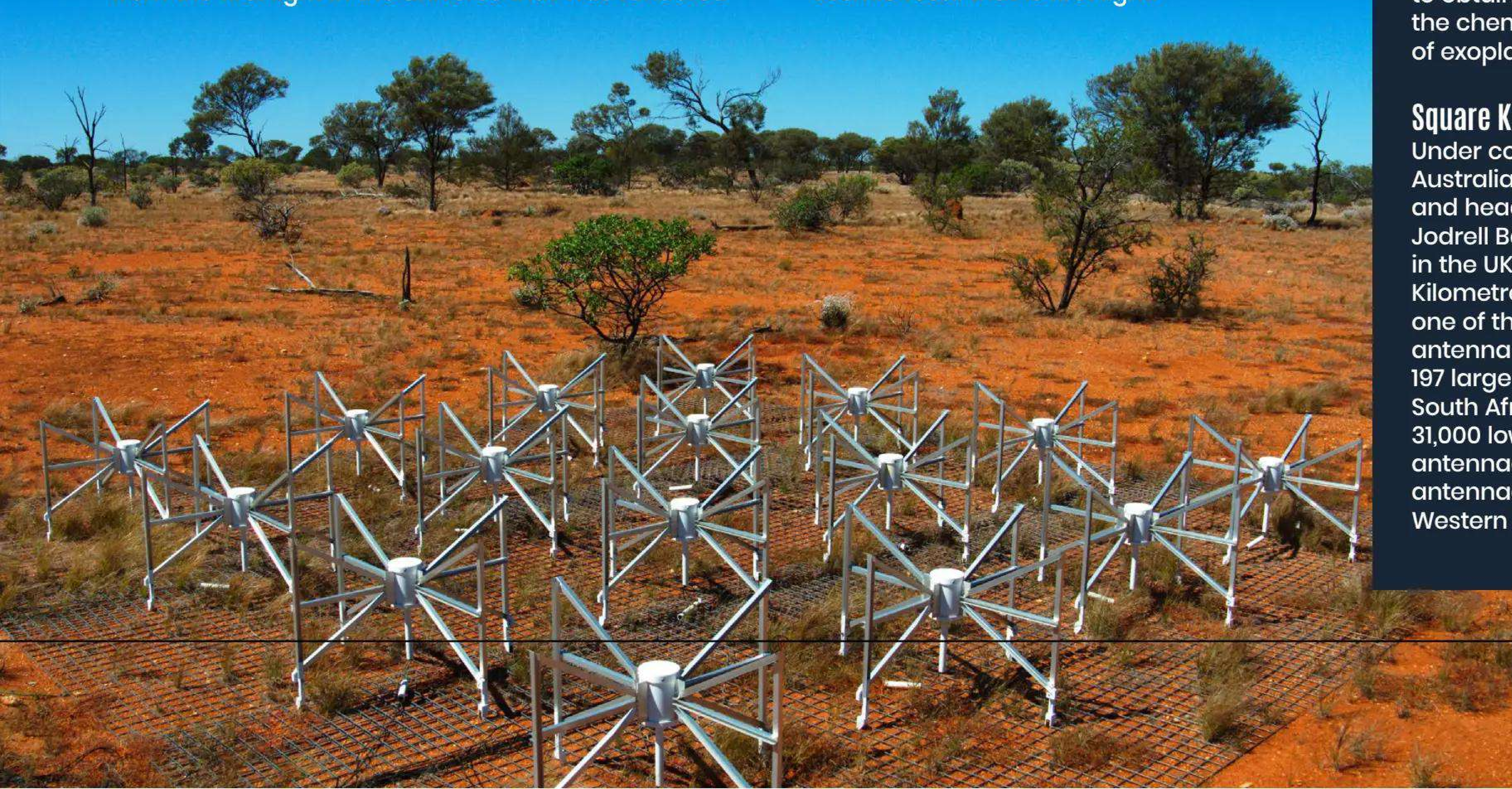
Some of the antennae of ASKAP, located in the desert of Australia

MWA defies the common image of what a telescope should look like

MURCHISON WIDEFIELD ARRAY

First light: 2013 **Location:** Western Australia
Type: Radio **Diameter:** Antennae spread over three kilometres (1.86 miles)

The Murchison Widefield Array (MWA) is composed of 4,096 spider-like antenna tiles attuned to the radio signals of the cosmos, redefining every preconception of what a telescope is. The antennae can be arranged into different patterns or configurations, with astronomers bringing them together to see large-scale or diffuse structures of the universe and spreading them apart to spot small-scale structures like galaxies in greater detail. One of its key aims is to find a signal from the first light in the universe that was rendered free to travel when the universe expanded and cooled enough to allow electrons to bond with protons and form the first atoms. During this so-called 'epoch of reionization', particles of light were no longer endlessly bounced around by free electrons, meaning the universe suddenly went from being opaque to transparent. The MWA aims to find a radio wave component from the cosmic fossil that is first light.



THE BEST IS YET TO COME

Vera C. Rubin Observatory

Currently under construction in Chile, the Vera C. Rubin Observatory is set to begin operations in 2025. Rubin will conduct the Legacy Survey of Space and Time (LSST), observing the entire visible southern sky every few nights over a decade, capturing 1,000 images of the sky each night. This will give scientists an exciting new view of the universe and its large-scale evolution.

Extremely Large Telescope

The Extremely Large Telescope (ELT) is under construction atop Cerro Armazones in the Atacama Desert. It will be the world's largest telescope in the visible to infrared wavelength range. The primary mirror of the ELT will be a whopping 39 metres (128 feet) across. Technical first light for the telescope is planned for the end of this decade.

Giant Magellan Telescope

Also under construction in the Atacama Desert is the Giant Magellan Telescope, a 25.4-metre (83.3-foot) telescope that will be based at Las Campanas Observatory. Operating in optical to infrared, the telescope will use seven of Earth's largest mirrors and a huge light-collection area to obtain information about the chemical composition of exoplanets.

Square Kilometre Array

Under construction in Australia and South Africa and headquartered at Jodrell Bank Observatory in the UK is the Square Kilometre Array. Phase one of the massive radio antenna array will consist of 197 large dish antennae in South Africa and a whopping 31,000 low-frequency wire antennae, similar to large TV antennae, in the desert of Western Australia.

FOCUS ON

THE JAMES WEBB SPACE TELESCOPE SPIES WATER NEAR THE CENTRE OF A PLANET-FORMING DISC

Some rocky worlds may have lots of water from birth

Reported by Charles Q. Choi

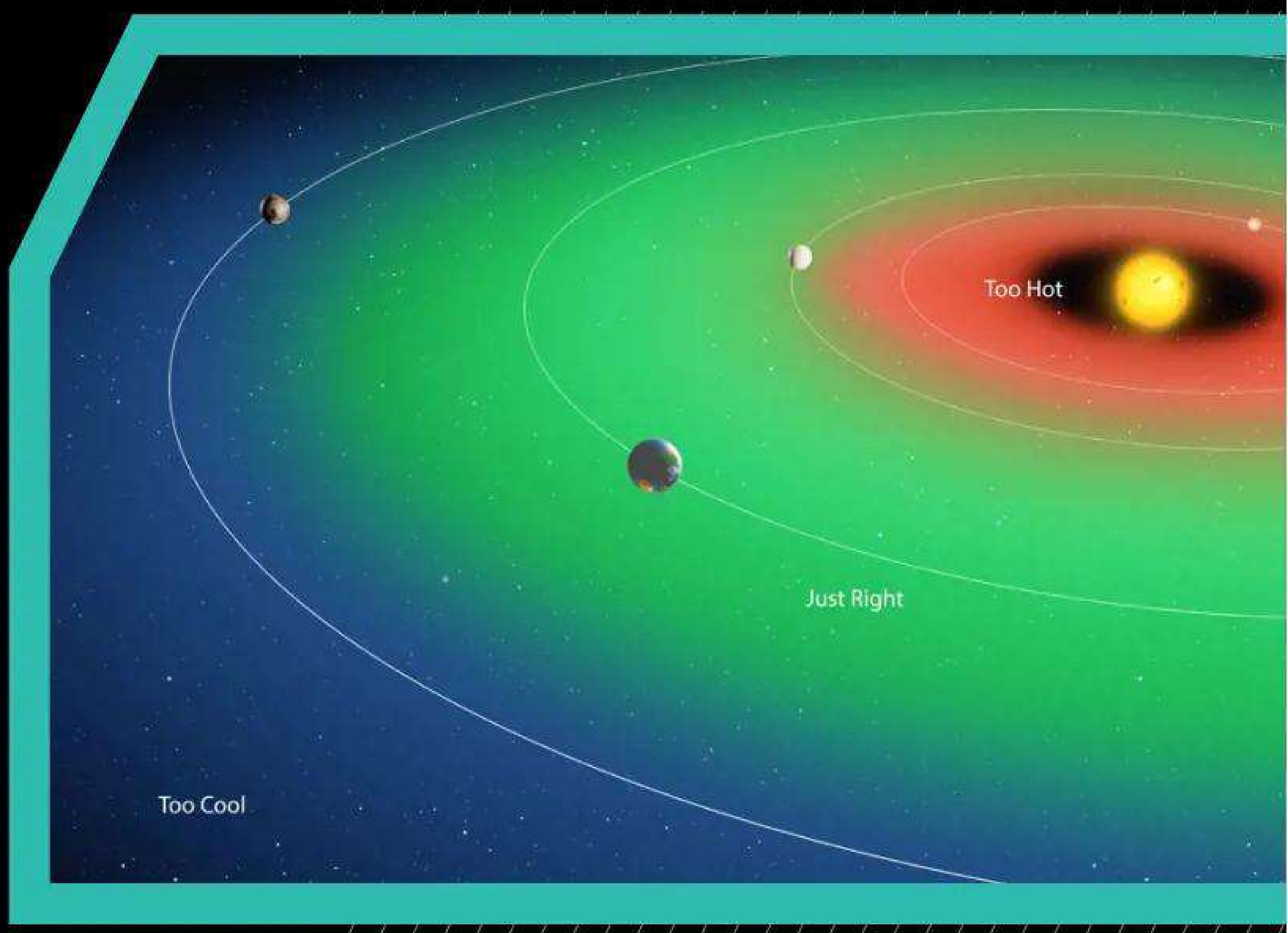
Astronomers have discovered that rocky alien worlds could possess large amounts of water from the moment they form. Life is found virtually wherever there is water on Earth. As such, the search for habitable exoplanets has mainly focused on hunting for the presence of water. Previous research suggested that the newborn Earth got a lot of its water from water-bearing asteroids bombarding our young planet's surface after it formed. Now scientists may have discovered evidence that water could also serve as one of the initial ingredients of rocky planets, available from birth.

Researchers focused on the young star PDS 70, located about 370 light years from Earth. About three-quarters the mass of the Sun, PDS 70 is only about 5.4 million years old, compared to our Sun's age of about 4.6 billion years. "PDS 70 is a star similar to our Sun, just younger and cooler," study lead Giulia Perotti, an astrophysicist at the Max Planck Institute for Astronomy, said. "By observing it, we can trace back how the planets in our Solar System formed and what their chemical composition was before they fully formed."

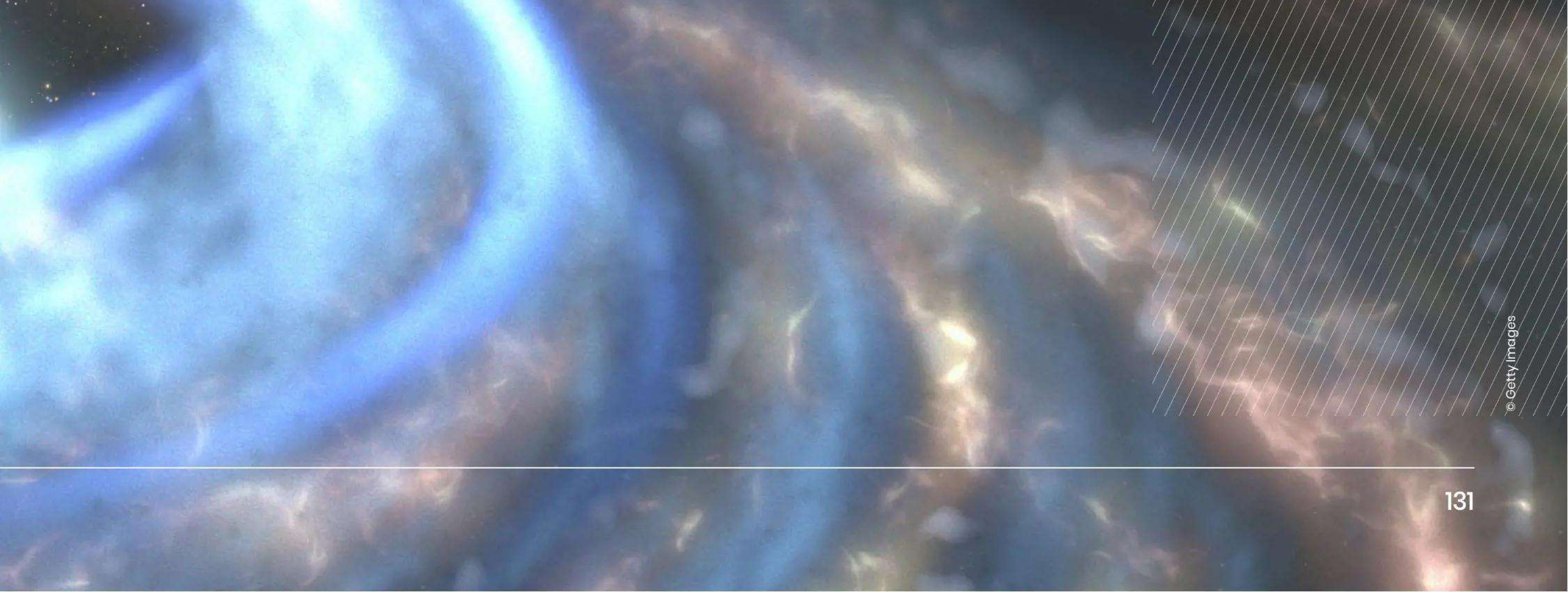
Using the Mid-Infrared Instrument (MIRI) on NASA's James Webb Space Telescope, the scientists discovered water near the centre of the planet-forming disc of gas and dust surrounding PDS 70, in the form of hot vapour. "Our result shows that water is present in the inner disc of this iconic system, where planets similar to Earth may be assembling," Perotti said.

In our Solar System, this central zone is where Earth and the other rocky planets formed. These new findings suggest that any rocky planets originating in PDS 70's central zone would draw from a substantial reservoir of water, improving their chances of habitability later on. PDS 70 is the first relatively old planet-forming disc where scientists have discovered water. Previous research failed to detect water in the central regions of discs of similar age, leading astronomers to speculate that harsh radiation from newborn stars might destroy nearly all water. But these new findings challenge that idea. "In the PDS 70 system, there's quite a lot of water available during the process of rocky planet formation," study co-lead Thomas Henning, an astrophysicist at the Max Planck Institute for Astronomy, said.

So far the scientists haven't actually detected any planets near the centre of PDS 70's disc. Discovering any such worlds requires larger telescopes, such as the Atacama Large Millimeter/submillimeter Array (ALMA) in Chile, Henning noted. Still, they have detected two gas giant planets farther out, dubbed PDS 70 b and c. The gravitational influence of these giant worlds is actually preventing the influx of ice-rich rock from the outer parts of the disc to its centre, Henning said. One possible explanation for the presence of this water is that it was left over from a water-rich nebula that gave birth to the PDS 70 system, with dust and other material in the planet-forming zone potentially shielding this water from the star's destructive radiation. Another possibility is that oxygen and hydrogen gas entering the outer rims of the PDS 70 disc might have combined to form water vapour that could in turn drift closer to the star. Future research could examine more planet-forming discs around young stars to see if PDS 70 is an unusual exception, Perotti said.



Liquid water can only exist within the habitable zone



EVERYTHING YOU NEED TO KNOW ABOUT EUCLID

This space telescope will shed light on the dark universe

Reported by Tariq Malik

The European Space Agency's (ESA) Euclid mission will map the geometry of matter in the universe – specifically the distribution of galaxies – to learn more about the parts of the universe we can't see: dark energy and dark matter. Euclid launched on 1 July at 15:12 (UTC) from Cape Canaveral, Florida, aboard a SpaceX Falcon 9 rocket. The mission aims to chart 1.5 billion galaxies over the past 10 billion years of cosmic history over its expected six-year lifetime.

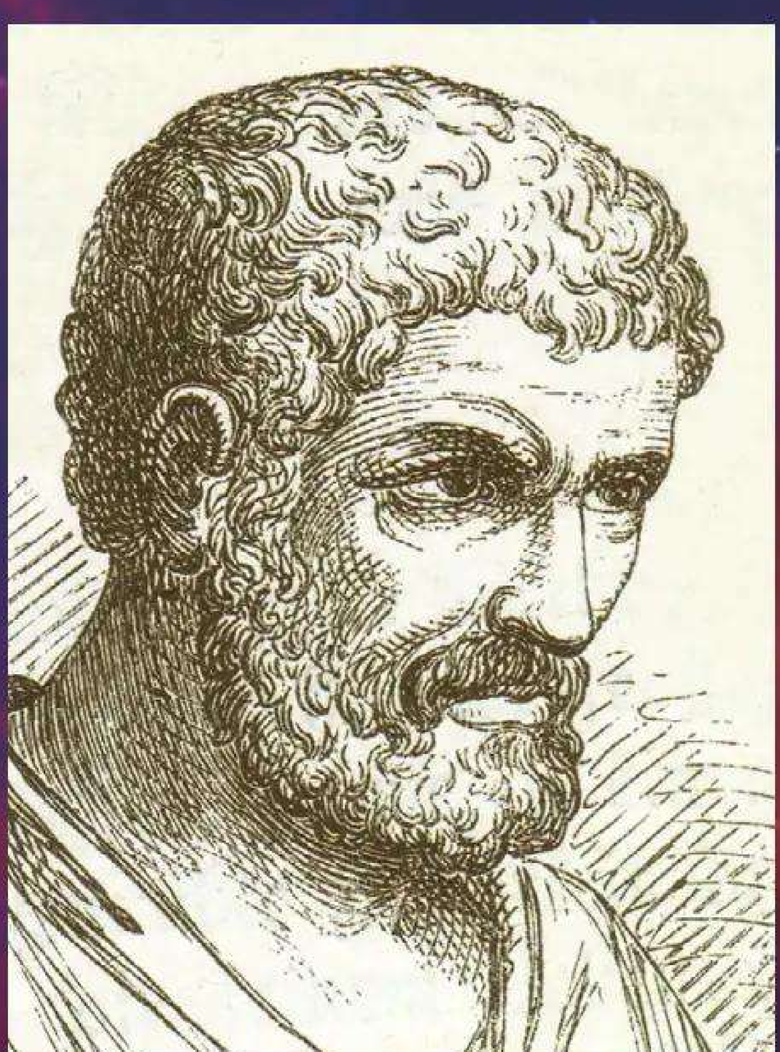
WHERE DID EUCLID GO?

It took roughly 30 days for Euclid to make its way to its destination at the L2 Lagrange point – the same location shared by several other spacecraft, including the James Webb Space Telescope. L2 lies about 1.5 million kilometres (930,000 miles) from Earth, but in the opposite direction to the Sun. It's a special location because it's at L2 that the gravity of Earth and the Sun balance, with the outwards centrifugal force acting on the spacecraft as it swings around Earth in its orbit. This makes the location quasi-stable – the spacecraft doesn't get flung deeper into space, but it does require manoeuvring thrusters for station keeping.

L2 also provides a clearer view of deep space, with the Earth, Moon and Sun always behind the spacecraft. This is essential if Euclid is going to succeed in its mission of charting 1.5 billion galaxies over the past 10 billion years of cosmic history, producing an image quality four times sharper than comparative ground-based surveys. As a survey mission, Euclid will last at least six years and cover 15,000 square degrees of sky. Its survey will be performed in a 'step-and-stare' mode, meaning that the telescope will point and make measurements on about 0.5 square degrees of the sky at a time.

WHO IS THE EUCLID MISSION NAMED AFTER?

It's fitting for a space mission that will be mapping the geometry of the universe to be named after the father of geometry. The Greek mathematician Euclid of Alexandria lived during the time of Alexander the Great, and although the known details of his life are sketchy at best, his legacy was the invention of geometry as a mathematical subject. Euclid invented what we refer to today as Euclidean geometry, which is the basis for mathematical fields such as trigonometry. The universe also has Euclidean geometry. Measurements by NASA's Wilkinson Microwave Anisotropy Probe (WMAP) show that the universe is 'flat' and does not have curvature like a sphere or a saddle. Parallel lines remain parallel forever, and the interior angles of triangles always add up to 180 degrees.



WHAT WILL EUCLID DO?

Euclid will show scientists more about the 'dark universe'. One of its main goals is to accurately map galaxy redshift – the stretching of light to redder wavelengths as an object moves away from us, as is the case as the universe expands in all directions. Hubble's law tells us that the distance to a galaxy is related to how fast the expansion of the universe is carrying that galaxy away from us, and the higher the recession velocity, the more distant the galaxy and the higher its redshift. Measuring this redshift tells astronomers the rate of the universe's expansion and the strength of dark energy as it accelerates that expansion. The mission will look back to galaxies that existed as long as 10 billion years ago, with a redshift of about 2.0, or more than double the Solar System's age. Over at least six years, Euclid will map about 36 per cent of the sky and perform an extra-deep survey across three smaller fields of the sky totalling 40 square degrees.

Euclid's detectors will conduct two cosmological probes. One will study weak gravitational lensing – the marginal bending of light by concentrations of matter. This is useful for mapping the location of dark matter around galaxies and galaxy clusters by measuring how much the galaxy images are distorted by lensing. The other probe will study baryonic acoustic oscillations (BAO), relics of fluctuations in the cosmic microwave background (CMB) radiation that today manifest themselves in the spatial distribution of galaxies. Across very large scales, galaxies tend to cluster in pairs separated by a standard distance. This standard distance is linked to sound waves in plasma, or ionised gas, in the early universe; the sound waves propagated as density waves through the plasma and are linked today to the locations of dark matter halos, or concentrations of dark matter associated with galaxies. The size of this standard distance increases over time as the universe expands, so BAOs are a standard ruler to measure the universe's expansion, and hence the strength of dark energy at different eras in cosmic history.

Q&A

GIUSEPPE RACCA

Racca is the European Space Agency's Euclid project manager

How will the Euclid mission improve our understanding of dark energy?

Dark energy is essentially a nickname for something that makes the universe expand in an accelerated fashion. This acceleration seems to have kicked off about 5 billion years ago and was discovered by observing from ground observatories the recession velocity of distant galaxies. The acceleration behaviour is consistent with a sort of 'repulsive' energy of the vacuum with constant density or a cosmological constant of the general relativity equations, which describe gravity as a matter versus space-time geometry relationship. Euclid will improve our understanding essentially by measuring whether the dark energy density is really constant over the last 10 billion years.

What will mapping galaxies teach us about dark matter?

Dark matter is the predominant form of matter in the universe. Without it, the stars probably wouldn't have formed in

ALL ABOUT THE EUCLID SPACECRAFT

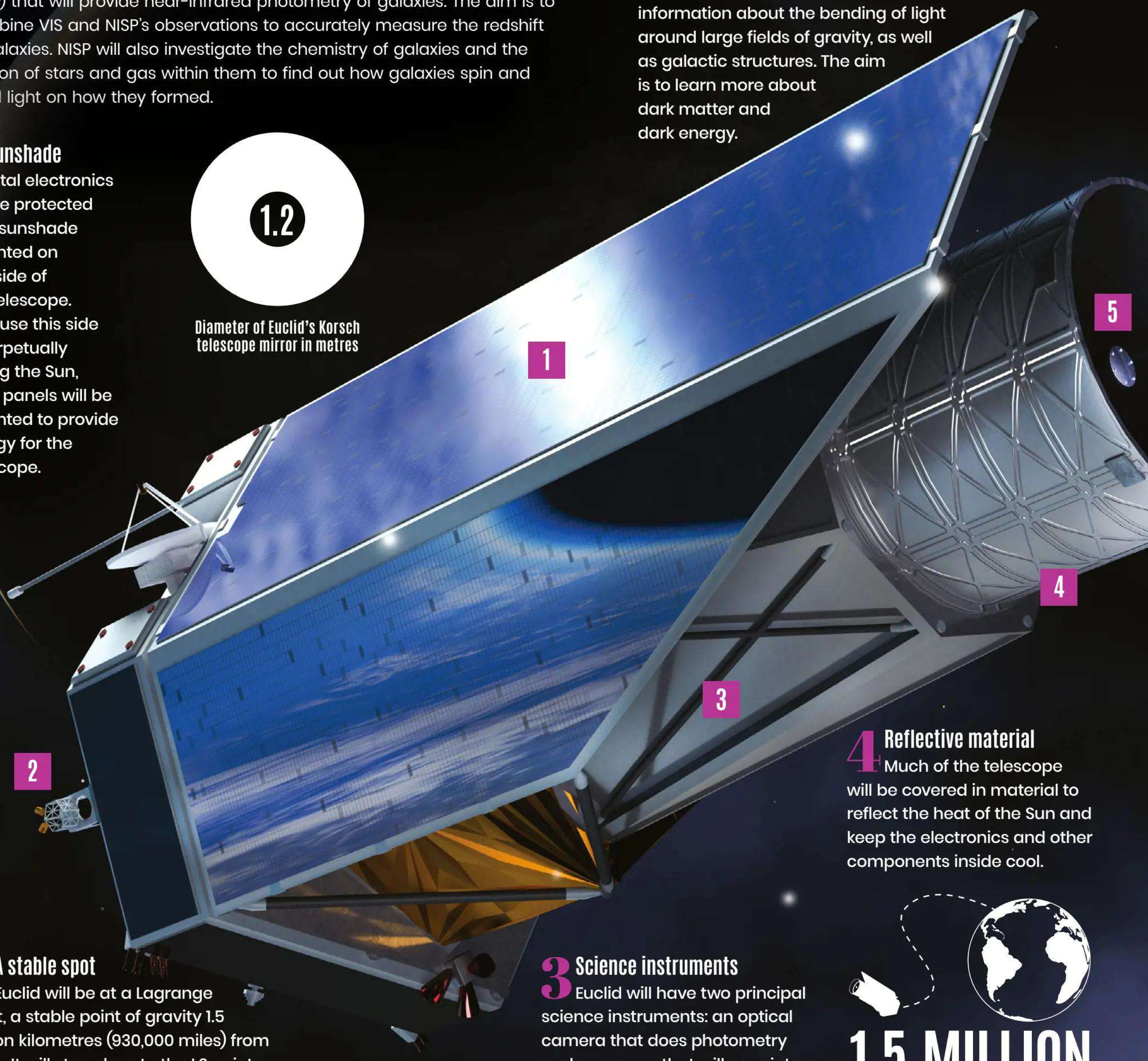
4.5 metres (14.7 feet) tall and 3.1 metres (10.2 feet) in diameter, Euclid is fairly modest compared to the size and complexity of the James Webb Space Telescope. Euclid's science will be performed by two instruments, and its onboard 1.2-metre (3.9-foot) telescope will capture and split light between them for analysis. One of these instruments is a visible imager (VIS), which will include 36 charge-coupled devices (CCDs) specially formulated for the mission. The field of view of VIS is 0.787 degrees by 0.709 degrees. The second instrument is a near-infrared spectrometer and photometer (NISP) that will provide near-infrared photometry of galaxies. The aim is to combine VIS and NISP's observations to accurately measure the redshift of galaxies. NISP will also investigate the chemistry of galaxies and the motion of stars and gas within them to find out how galaxies spin and shed light on how they formed.

0.36 The total area of sky that Euclid will observe during its 6.5-year mission life

850 The number of gigabits of compressed data that Euclid will collect per day

10 BILLION The number of years into the universe's past that Euclid will look into

1.2 Diameter of Euclid's Korsch telescope mirror in metres



1 Sunshade
Vital electronics will be protected by a sunshade mounted on one side of the telescope. Because this side is perpetually facing the Sun, solar panels will be mounted to provide energy for the telescope.

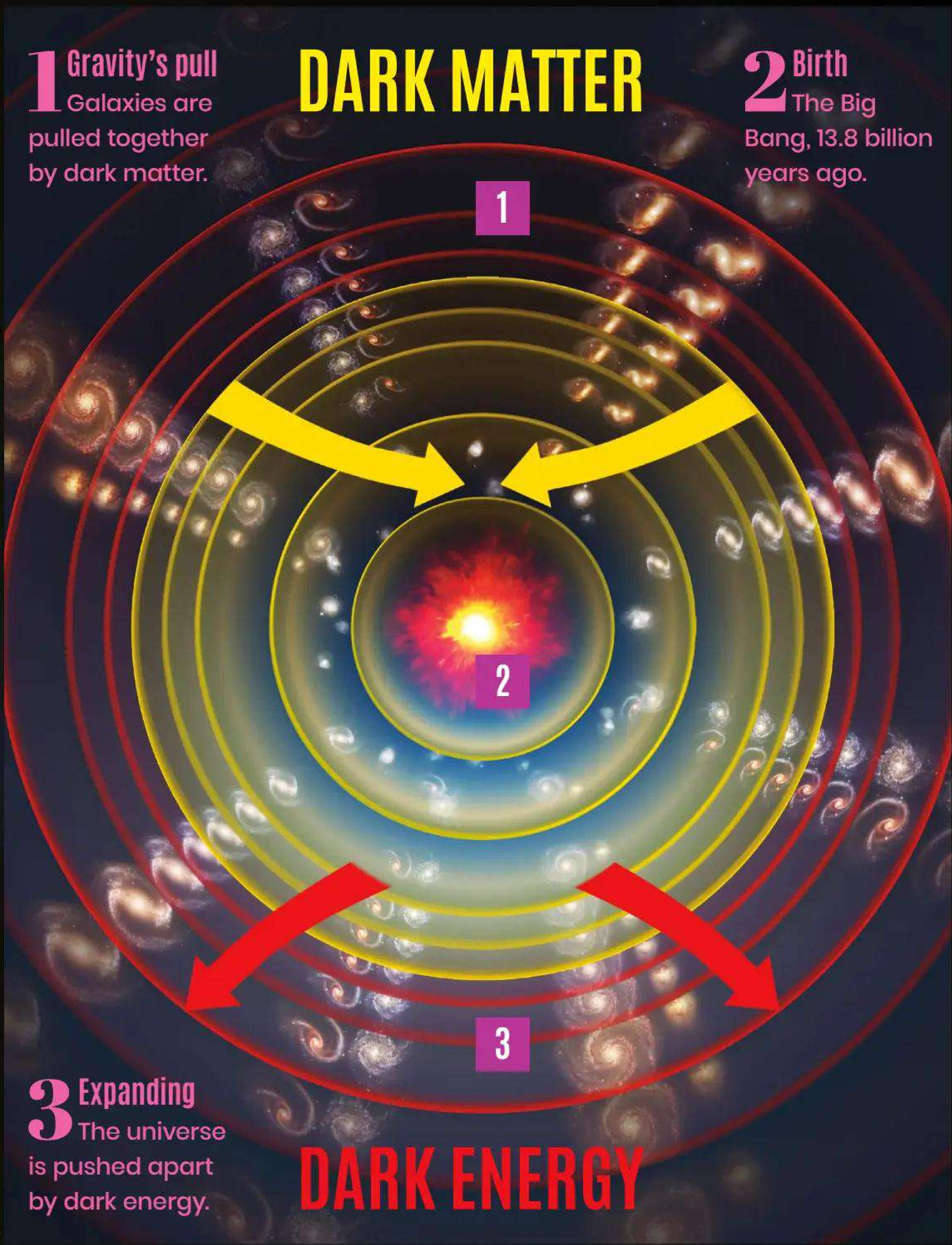
2 A stable spot
Euclid will be at a Lagrange point, a stable point of gravity 1.5 million kilometres (930,000 miles) from Earth. It will stay close to the L2 point, remaining relatively stationary except for occasional adjustments.

3 Science instruments
Euclid will have two principal science instruments: an optical camera that does photometry and a camera that will peer into the near-infrared, performing photometry and spectrometry.

4 Reflective material
Much of the telescope will be covered in material to reflect the heat of the Sun and keep the electronics and other components inside cool.

5 Telescope mirror
A large mirror will collect information about the bending of light around large fields of gravity, as well as galactic structures. The aim is to learn more about dark matter and dark energy.

1.5 MILLION Euclid's distance, in kilometres, from Earth in its operational orbit



WHAT ARE DARK MATTER AND DARK ENERGY?

Dark energy and dark matter make up most of the mass and energy in the universe. Dark matter is an unseen substance, the presence of which we can only infer from its gravity. Dark matter contributes about 26.8 per cent of all the matter and energy in the universe. Dark energy, on the other hand, is a mysterious energy field that's accelerating the expansion of the cosmos and accounts for about 68.3 per cent of all the mass and energy in the universe. The remaining 4.9 per cent is everything else that we can see in the universe – people, planets, stars, nebulae and galaxies. Together, dark matter and dark energy affect the geometry of the universe. Clumps of dark matter create gravitational wells that can bend the otherwise straight paths of light from more distant objects, while by driving the accelerated expansion of the universe, dark energy pulls clumps of matter away from one another, lowering the overall density of matter in the cosmos. By measuring how they affect the universe, astronomers can gain important insights into their puzzling natures.

the early universe, and the presence of dark matter across the universe is essential to all cosmic structure formation. Dark matter is not visible and does not absorb radiation, but deflects light because of its gravitational pull – more exactly because of its warping of space-time – and deforms the shape of the galaxies as seen by the observer. This effect is called weak gravitational lensing. By observing distant galaxies whose light has travelled through the dark and regular matter from the source to us, we can measure the distribution of dark matter in its path. By doing this with billions of galaxies, Euclid will build a full map of the distribution of dark matter in the entire universe.

"Dark matter is not visible and does not absorb radiation"

How does Euclid differ from other dark energy studies?
There are indeed many cosmological surveys, mainly on the ground and one planned from space – NASA's Roman Telescope. Euclid's quality is in its image sharpness, which allows it to minimise the systematic errors concerning the aforementioned weak lensing probe. Moreover, the Euclid telescope's characteristic design allows it to cover a large amount of the sky in a relatively short time with unprecedented accuracy and precision. Concerning the spectroscopic capability, Euclid will also make observations of light from galaxies at near-infrared wavelengths, which is absorbed by the atmosphere and therefore not visible from the ground. This capability is used to accurately measure the recession velocity of hundreds of millions of galaxies as far as 10 billion light years.

FASTER THAN THE SPEED OF LIGHT

The speed of light is the universe's ultimate speed limit, but could there be a way to get around it?

Reported by Giles Sparrow

Pick up any book on physics or astronomy and you'll read that light is the fastest thing in the universe and that immutable laws prevent anything else from ever matching its speed through space. The limited speed of light sets the rules of cause and effect across the universe, and even affects how we see the distant cosmos. But what are the rules behind this cosmological speed limit? How exactly does it apply? Could there be natural phenomena that break this apparently universal rule, and might we one day find a way of doing the same?

Light travels through an empty vacuum with astonishing speed, crossing 299,792 kilometres (186,282 miles) of empty space in a single second. This means that light – and other related forms of electromagnetic radiation such as radio waves – seem to move instantaneously; it's only when we look into the depths of space that the effects of its finite speed become apparent. Radio commands sent to rovers on Mars may take up to 20 minutes to reach the Red Planet, while light from the nearest stars has travelled several years to reach us. Distant galaxies are hundreds of millions and even billions of 'light years' away.

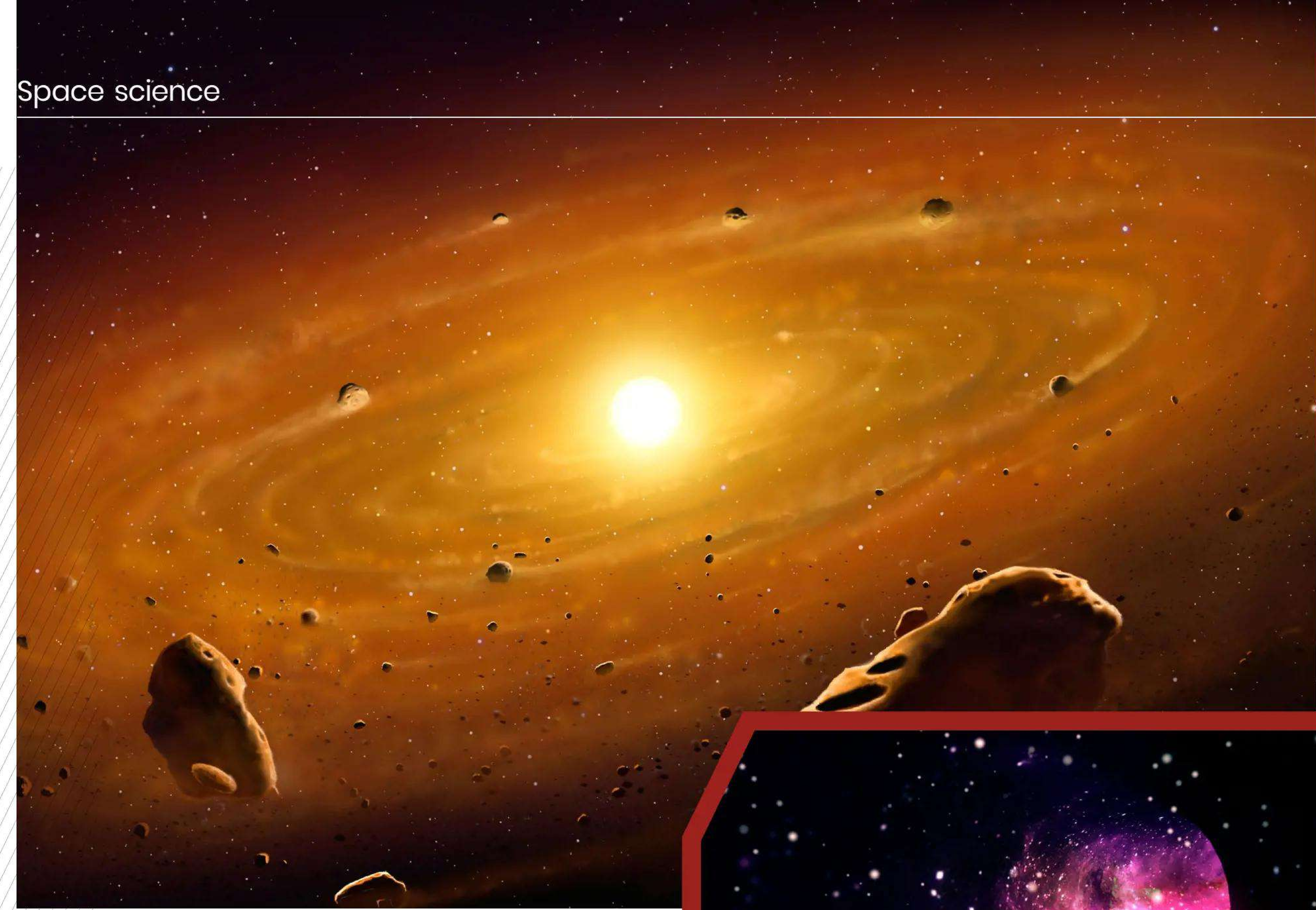
The idea of the speed of light as an ultimate cosmic speed limit only emerged around 1905 through Albert Einstein's special theory of relativity. "We'd had, at that point in the early 20th century, a fairly complete theory of classical electromagnetism for about 40 years or so," explains Dr Erik Lentz, a physicist at the Pacific Northwest National Laboratory (PNNL) in Washington. "And so Einstein had a notion of how electromagnetic fields could create a propagating light beam that travelled at a particular speed. But that speed, interestingly, didn't seem to depend on what frame of reference you calculated it from. Whether someone was trying to measure the speed of a light beam relative to themselves in a laboratory or on board a moving train, it didn't seem to matter."

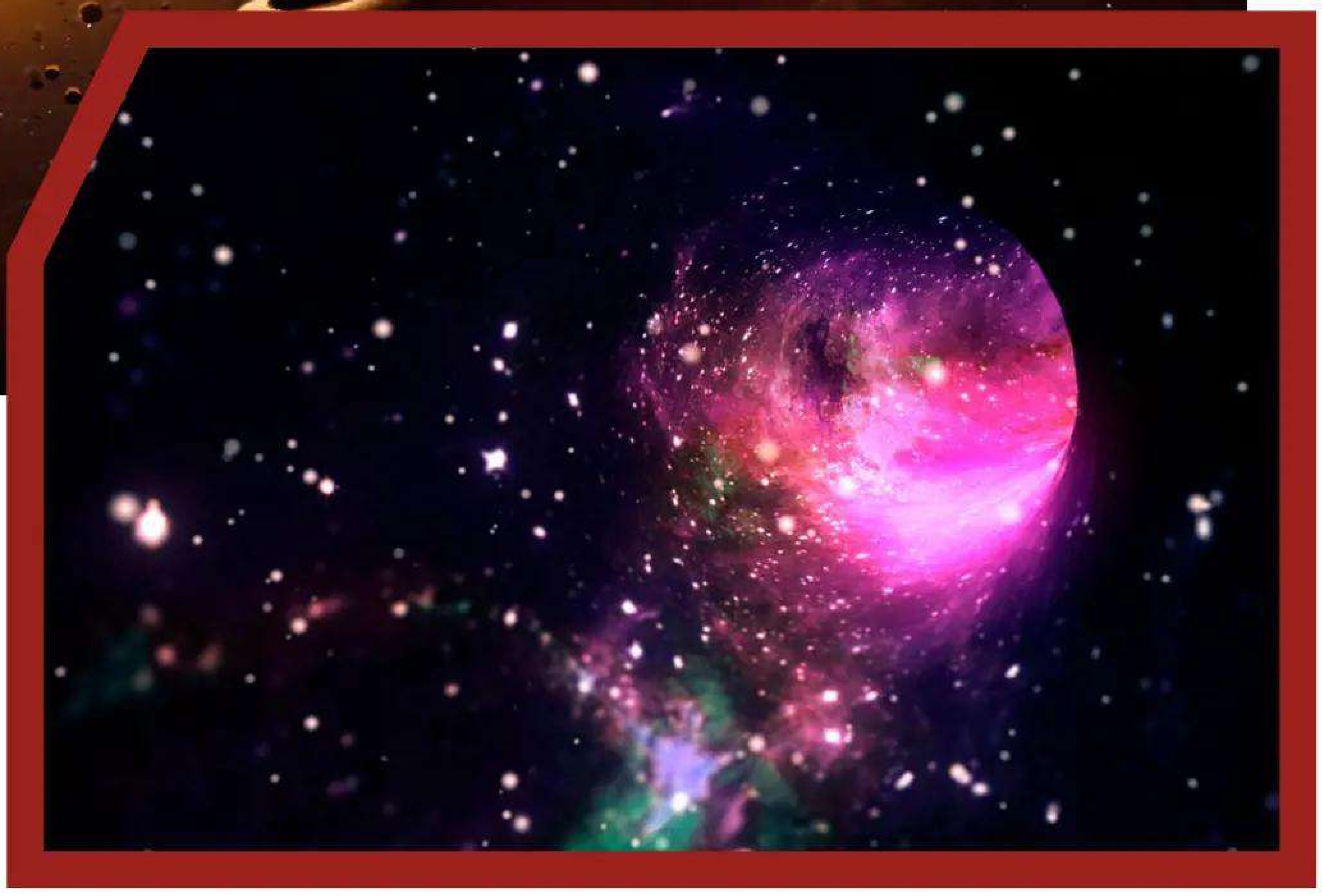
Einstein's special theory described how this fixed or 'invariant' speed of light can affect other types of measurements, usually in circumstances where two objects are moving at very high or 'relativistic' speeds in relation to each other. For instance, objects moving at high speeds relative to an outside observer appear shortened along their direction of travel, experience time dilation and even increase their mass rather than

FASTER-THAN-LIGHT PARTICLES?

The laws of relativity make it impossible for matter particles to reach the speed of light, but they don't rule out the idea of particles that naturally exist on the other side of this barrier. Some physicists argue there could be a whole universe of such faster-than-light particles, known as tachyons. They would have very unusual properties compared to normal matter. For instance, their speed would decrease as their energy increased, and it would take an infinite amount of energy to slow them down to the speed of light.

But most scientists remain doubtful. Some argue that the existence of tachyons would offer a way around the fundamental rule of cause and effect. This is because from our point of view, tachyons could theoretically carry signals backwards in time, giving rise to all sorts of paradoxes.





their velocity as they attempt to reach the speed of light. These factors all increase exponentially as an object gets closer and closer to the speed of light, making it impossible for any object with mass to actually travel at the speed of light relative to another frame of reference – light itself can only do so because it's a massless electromagnetic wave.

But the special theory is just part of the story. As the name suggests, it only applies to movement in certain situations, namely those where objects are neither accelerating or decelerating. Einstein's general theory of 1915 expanded to take in a wider range of scenarios and also tackled the effects of gravity, which can be treated as a form of acceleration. One consequence was that movement in time and the three previously rigid dimensions of space could be better considered in terms of a more flexible four-dimensional structure known as space-time. "In the generalised form of relativity, those principles started to become localised," expands Lentz. "You had to change your statement from 'no two things can travel faster than the speed of light' to 'no two things moving relative to each other at a particular point in space can move past each other faster than the speed of light. But once you start to think about separating two bodies, then those statements no longer become exactly relevant. You can use the dynamics of space-time in order to change the separation of those bodies at potentially arbitrary speed."

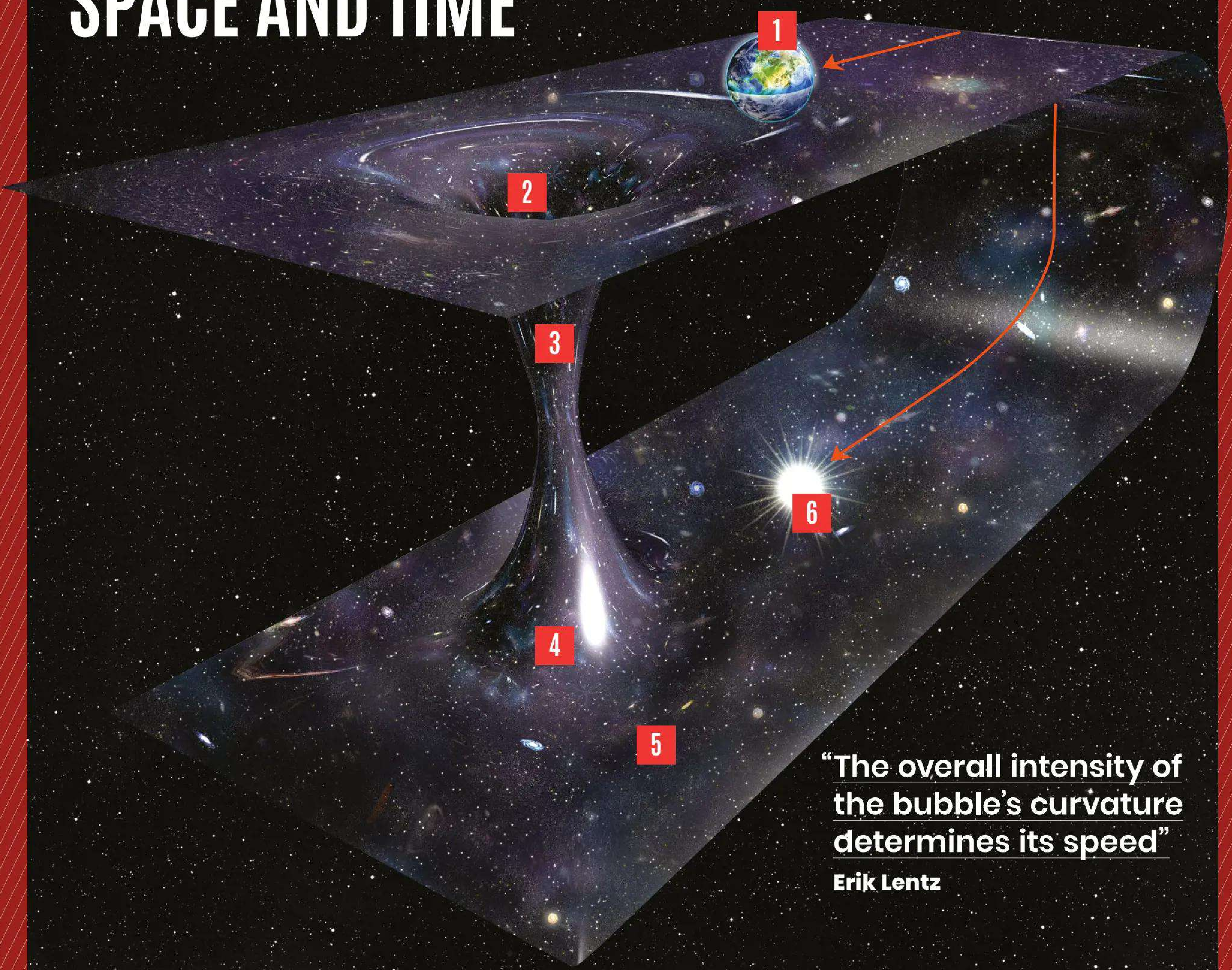
For an example familiar to many space enthusiasts, consider looking out across billions of light years into the depths of intergalactic space. We've known for almost a century that the universe is rapidly expanding, and that the further away a distant galaxy is, the faster it tends to be moving away from Earth. This effect is mostly due not to the motion of galaxies through space, but to the expansion of space between them ever since the Big Bang. Each unit of space itself is growing at a more or less uniform rate, and so more widely separated objects, with a greater amount of space between them, are driven apart more rapidly. From our point of view, this means that beyond a certain distance, galaxies will be moving away faster than the speed of light. However, because this means their light can never reach Earth, such objects lie forever beyond our 'observable universe'.

For many people, however, the question of breaking the light-speed barrier is a more practical one: could humans – or indeed extraterrestrials – ever hope to find a means of faster-than-light travel to bridge the vast distances between stars and galaxies? If the only concern is for the length of the journey from the crew's point of view, then relativity already provides a solution in the

Shortly after the Big Bang, a vast release of energy blew up space in an event called inflation

Wormholes connecting different parts of the universe offer a potential means of travelling faster than light

TRAVELLING THROUGH SPACE AND TIME



> "The overall intensity of the bubble's curvature determines its speed"
> **Erik Lentz**

1 Home near a wormhole

To allow for truly convenient interstellar travel, a wormhole would have to be located – or created – quite close to Earth, otherwise it would take many years to reach in the first place.

2 Down the funnel

The mouth of a wormhole forms a steep-sided 'gravity well', but there's a safe entrance that avoids crossing the event horizon.

3 Through the gap

Crucially, the passage through the wormhole is 'open' – it forms a broad cylindrical tunnel so that the crushing gravity of the central singularity can be avoided.

4 Not-so-short cut?

The trip might be shorter, but it's still not instantaneous. Because going through might still involve near-light speeds, effects such as time dilation would make the journey seem shorter.

5 Safe passage

In theory, it's possible to steer a passage that hugs the outer edge of the wormhole to emerge at the other end.

6 Other places and times?

The other end of the wormhole emerges near a distant star. Depending on exactly how the universe works, it might even form a tunnel through the fourth dimension of time as well.

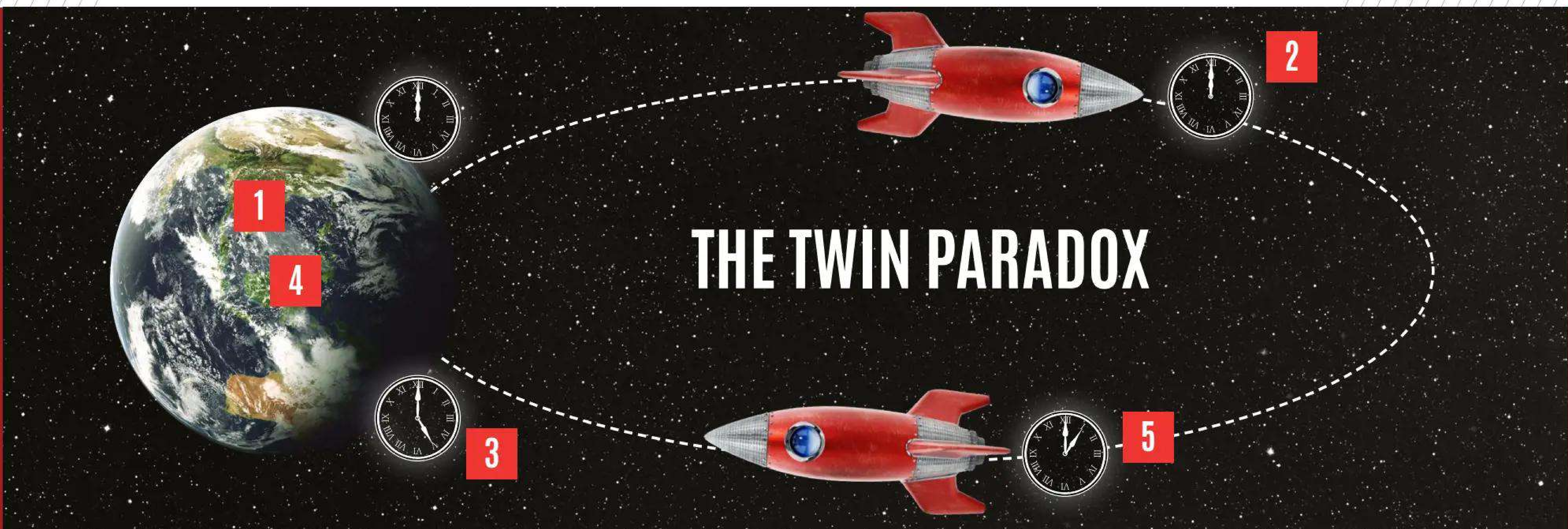
form of time dilation. As seen from outside, time for a fast-moving spaceship will appear to flow much more slowly; a trip to a nearby star might be accomplished in a matter of weeks, or even less, and the crew might at first think they'd travelled faster than light. Upon arrival at their destination, however, they'd be able to measure how much time had passed for the rest of the universe.

A more fantastical form of 'true' faster-than-light travel might be a wormhole across space-time – a tunnel linking one area of the universe to another via a cosmic shortcut. Wormholes are a popular concept in science fiction and can, at least in theory, arise naturally according to the laws of relativity. For instance, they might form when a massive, superdense object distorts the space around it to create a 'gravitational well' in the fabric of space-time that connects to a similar well in another location. Some cosmologists have speculated that tiny natural wormholes could riddle the universe, but creating an artificial one with a wide enough tunnel for spacecraft to fly safely through would represent a huge challenge for even the most advanced cosmic civilisation – and a single wormhole could only link two locations.

Perhaps the most intriguing and versatile form of faster-than-light travel is the warp drive. More than a little reminiscent of the technology used by the USS Enterprise and many other science-fiction starships, a warp drive creates a distorted bubble of space that can move through its surroundings at faster-than-light speeds while carrying a spacecraft in a relatively normal region of space embedded within it. Lentz traces the origins of the idea back to the work of Mexican physicist Miguel Alcubierre in the 1990s. Alcubierre took inspiration from the theory of inflation – an early cosmic growth spurt that followed the Big Bang, during which the universe briefly expanded far faster than the speed of light, pushing the bulk of the newborn cosmos forever beyond our view. "There was this precedent in cosmology for thinking about objects that could separate at a very high rate from one another," recounts Lentz. "And so Alcubierre constructed this space-time geometry. He engineered, in a theoretical way, a space-time metric to create a localised region, or bubble, with a spherical shape. And this entire spherical region could move through space-time at an arbitrary speed while maintaining in its centre a region of locally 'flat' space-time – a nice, calm space where you could put an observer inside a relatively unobtrusive spacecraft."

In Alcubierre's concept, space behind the warp bubble would expand at inflation-like, faster-than-light speeds, while space in front would be contracted at a similar rate, propelling the bubble forwards. "The observer wouldn't necessarily feel any

> "This spherical region could move through space-time at an arbitrary speed while maintaining in its centre a region of locally 'flat' space-time"
> **Erik Lentz**



1 Stay-at-home twin We start out with a pair of identical twins. One remains on Earth.

2 Interstellar traveller The second twin bids the other farewell as they set out on an interstellar trip, travelling close to the speed of light.

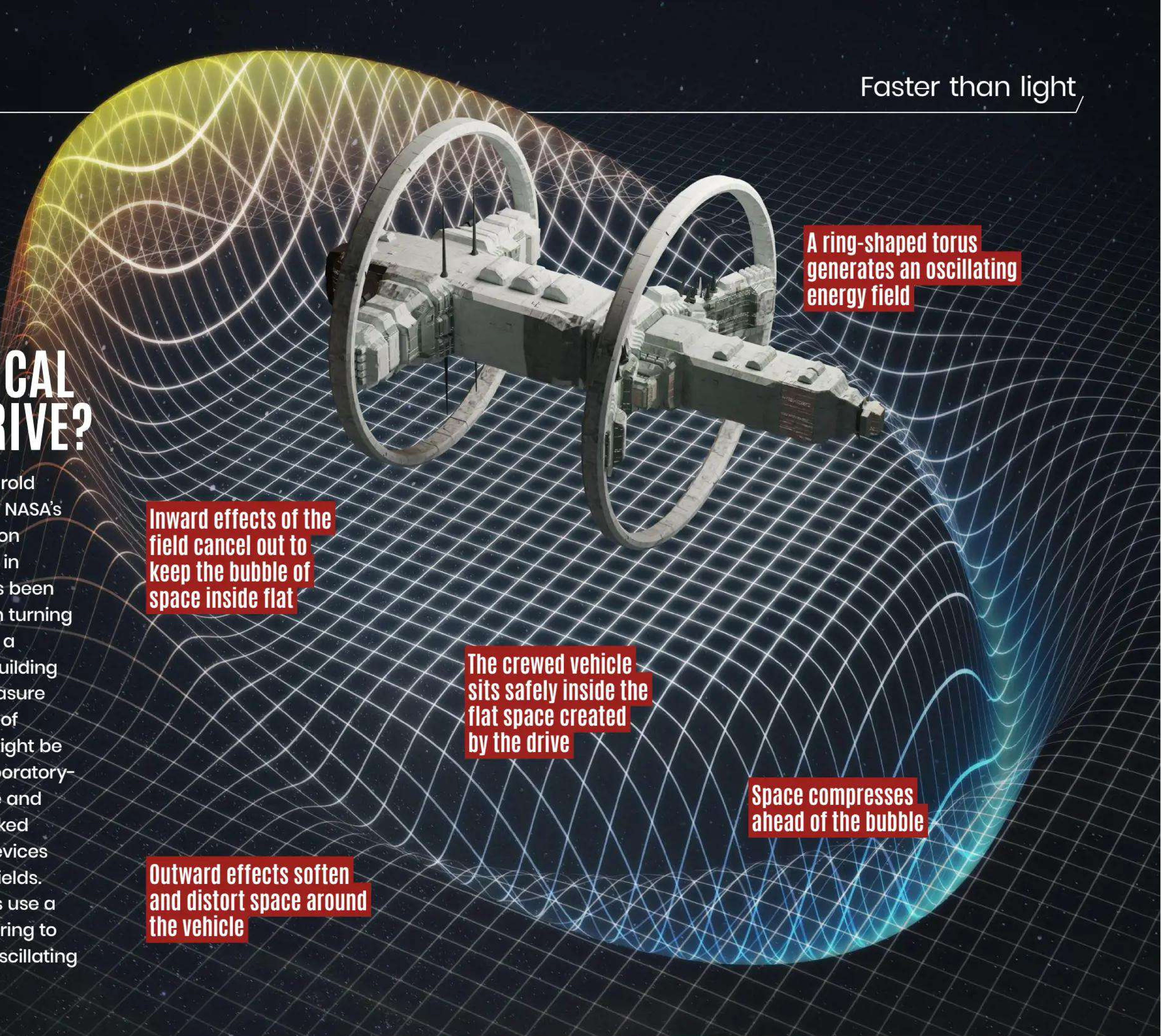
3 The paradox Only the traveller experiences acceleration during the experiment.

4 Years later The twin on Earth has experienced decades of time and grown old by the time the sibling returns.

5 Returning voyager Thanks to time dilation, the travelling twin has experienced just a few months' passage of time during their trip to the stars.

A PRACTICAL WARP DRIVE?

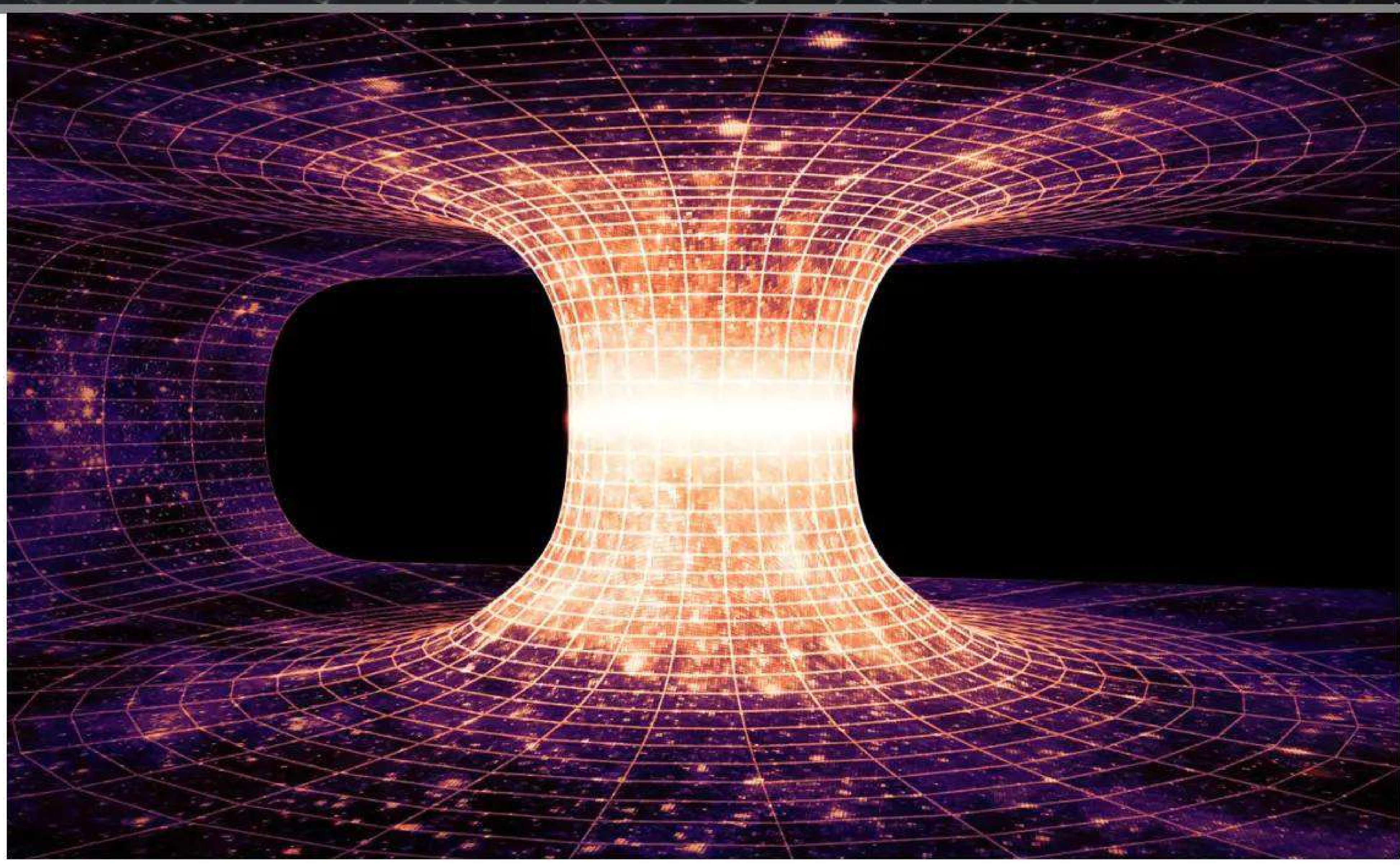
Led by physicist Harold G. White, a team at NASA's Advanced Propulsion Physics Laboratory in Houston, Texas, has been steadily working on turning the warp drive into a reality. As well as building instruments to measure the tiny distortions of space-time that might be generated by a laboratory-scale device, White and his colleagues worked on the design of devices to generate warp fields. Their latest designs use a doughnut-shaped ring to contain a rapidly oscillating energy field.



sensation of motion," Lentz points out, "but afterwards they would have this notion that they started at point A and ended at point B, and the rate at which the observer travelled between them indicated that they had moved faster than light."

By moving an area of space-time complete with its contents rather than accelerating a specific object, the Alcubierre warp drive overcomes many problems presented by relativity and light's speed limit. But there are major challenges to turning this neat theoretical idea into reality. Perhaps the most immediate is how to construct the bubble in the first place, and the fact that in order to retain a stable shape it must have a negative energy density in comparison to the space around it. At first this might sound impossible. Space-time naturally carries a very small amount of positive 'vacuum energy', but laboratory experiments have generated small regions with even lower energy densities, which are therefore 'negative' compared to their surroundings. The challenge lies in creating negative energy on a much larger scale, and early calculations suggested this would require harnessing more power than is present in the entire observable universe.

"There has been follow-up work after Alcubierre put out his paper to try and bring this number down," Lentz points out. "And there's been a decent amount of success, but it still requires the manipulation of negative energy equivalent in magnitude to that of a small asteroid." That is, the energy that would be released if that asteroid's entire mass could be transformed into pure energy. "And again, with the Alcubierre-like solution,



^ Massive objects create dents in space-time – distortions we experience as gravity. A wormhole is a hypothetical bridge formed when two of these dents in different parts of space connected

we still have a problem of a sort in terms of whether or not we're even able to make the more exotic negative energy media."

In 2020, while working at Germany's Göttingen University, Lentz found himself drawn back to the problem, paving the way for a potential new solution. "Every single one of these warp drive papers using general relativity seemed to require this exotic negative energy density in one form or another. I wanted to see if you could change that, if you could try and make a solution in the context of general relativity that could travel at arbitrary speed – meaning either below or possibly above the speed of light – that didn't require exotic media, or at least it didn't require negative energy. And after a bit of work, I believe I came up with such a solution."

Lentz's version of the warp drive creates a bubble within a moving wave-like structure in space-time, rather than Alcubierre's simple sphere. "It had many more subdomains to it," he recalls, "and the sourcing function – where the mass and energy would need to be and the shapes that they would need to be configured in – was also a bit more complicated than Alcubierre's original solution. But by exploring this larger and more complex set of space-times, which involved a lot of trial and error, I found some geometries that appeared to do the job."

By flipping the energy density required in the distorted space from negative to positive, Lentz's work seems to make the construction of a warp drive far more plausible – but how exactly would it work? For instance, how could the speed of movement be controlled? "The overall intensity of the bubble's curvature determines its speed," explains Lentz. "So you can make a bubble that's relatively non-intense and would travel at a slow speed – much slower than the speed of light, which I think is how any experimental verification would happen. You'd make a very low-intensity version of a bubble to demonstrate that this sort of manipulation of space-time can occur in a laboratory setting long before you'd think of making a functional warp drive for a spacecraft."

While Lentz's new role at PNNL has drawn him away from work on warp drives, his breakthrough has already inspired other physicists to revisit the idea with fresh approaches, and he's keen to return to the area in the future himself to resolve some unanswered questions. In particular, passing through the light-speed barrier seems to generate a 'horizon' – a communication barrier sealing off the region being transported from the rest of the universe. "If there is a horizon, how would you communicate with the rest of the bubble in order to bring your speed up or down?" he ponders. It's certainly an intriguing idea. We might one day be able to cross the universe faster than the speed of light, but be unable to put it to practical use because we can't reach the brakes.

Giles Sparrow
Space science writer
The author of over 20 books on popular science, Giles holds a degree in astronomy and is an editor specialising in science and technology.

The most distant galaxies we can see are moving away from us at speeds approaching the speed of light thanks to cosmic expansion

FOCUS ON

NASA SHUTS DOWN ITS NEOWISE ASTEROID HUNTER AFTER ALMOST 15 YEARS IN SPACE

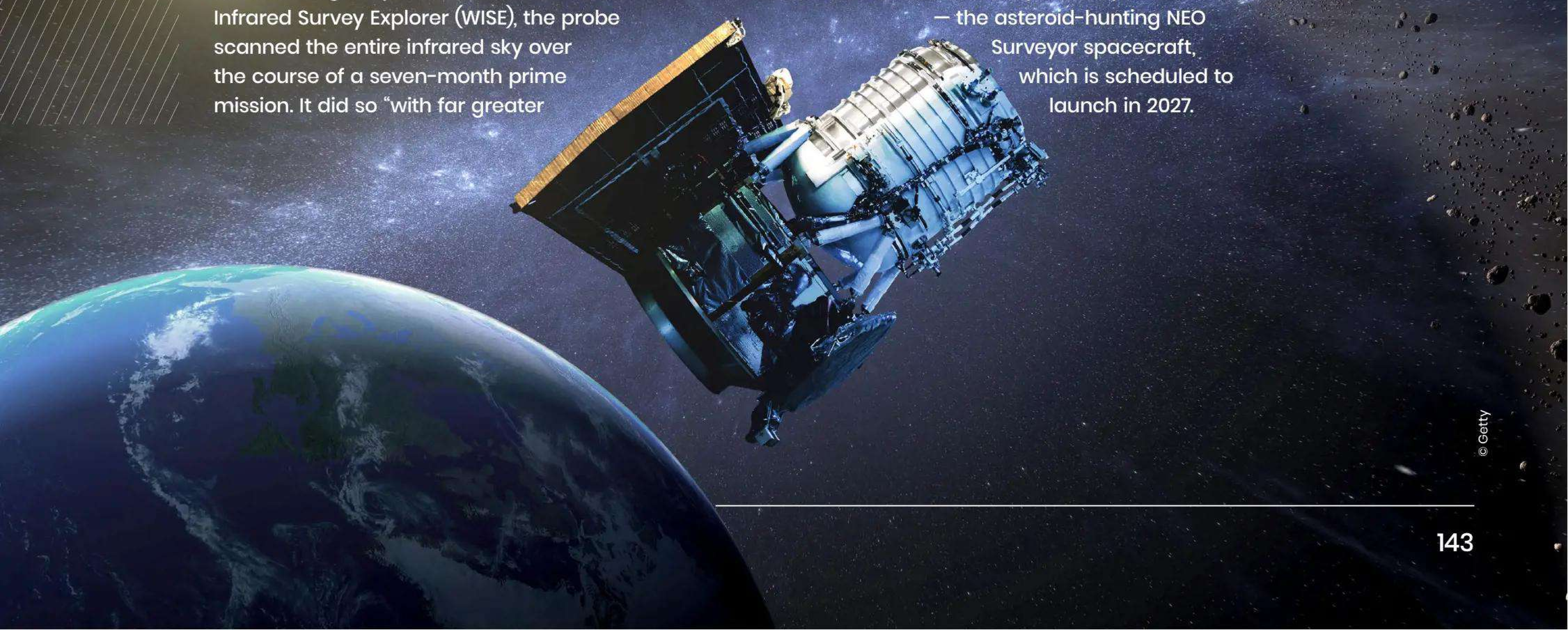
The mission has helped lay the foundations for its successor in the field of planetary defence

Reported by Mike Wall

A prolific asteroid-hunting mission has come to an end. NASA engineers sent a final command to the Near-Earth Object Wide-field Infrared Survey Explorer (NEOWISE) on 8 August, ordering the probe to turn off its transmitter after nearly 15 years of operation. "The NEOWISE mission has been an extraordinary success story as it helped us better understand our place in the universe by tracking asteroids and comets that could be hazardous for us on Earth," Nicola Fox, associate administrator for the Science Mission Directorate at NASA, said. "While we are sad to see this mission come to an end, we are excited for the future scientific discoveries it has opened by setting the foundation for the next-generation planetary defence telescope."

NEOWISE launched in December 2009 with a different name and a different mission. Originally called the Wide-field Infrared Survey Explorer (WISE), the probe scanned the entire infrared sky over the course of a seven-month prime mission. It did so "with far greater sensitivity than previous surveys," NASA officials wrote in a statement. In 2010, WISE ran out of coolant. As a result, the probe could no longer mitigate the heat produced by its own operations, which interfered with its detailed infrared observations of the deep cosmos. But that wasn't a death blow for WISE. NASA granted the probe an extended mission called NEOWISE, during which it conducted a survey of the objects in the main asteroid belt between Mars and Jupiter.

NASA put NEOWISE into hibernation in February 2011, but reactivated it two years later after determining that the probe was still capable of observing asteroids and comets that zoom close to Earth and sport a strong infrared signal thanks to solar heating. NEOWISE did this work for the next 11 years, making a slew of discoveries in the process. The mission spotted more than 3,000 near-Earth objects – 215 of which were previously unknown to astronomers. NEOWISE also discovered 25 comets, including Comet NEOWISE, or C/2020 F3, which put on a show for skywatchers in the summer of 2020. The mission also helped lay the foundations for its successor in the field of planetary defence — the asteroid-hunting NEO Surveyor spacecraft, which is scheduled to launch in 2027.



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